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Research Article

Reliability analysis of a mounted moldboard plow structure using the Monte Carlo simulation method

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ABSTRACT- Applying the reliability concept as a new and profitable design approach can optimize the design and manufacturing of tillage machines. In this study, the Monte Carlo method was used to perform reliability analysis on the whole chassis of a moldboard plow. For this, a complete model of a three-bottom moldboard plow was assumed as the limit mode function. Stochastic soil parameters were applied and the interaction forces of the plow with soil were simulated with finite element method (FEM). The desired output was the soil reaction forces on the plow at the most critical plowing speed and depth. Then, by applying the forces obtained from the FEM model and considering Young's modulus of the chassis as a random variable, chassis static analysis was performed in different iterations and the stress concentration at different locations was determined. The probability of failure (P_f) and reliability index (β) of different locations of chassis were calculated. The results of the Monte Carlo simulation showed that the highest P_f occurred in crossbars, standards, braces and, masts with the values of 1, 0.296, 0.165 and, 0.033, respectively, which indicates the uncertainty of the design in these parts and the needs to strengthen or optimize the aforementioned parts of the moldboard plow chassis.

INTRODUCTION

The design of structures in engineering is mostly based on deterministic methods. However, in practice, many parameters have high degrees of uncertainties in their nature. These uncertainties are basically attributed to changes in applied loads and material properties (Ditlevsen and Madsen, 2005). Two approaches including deterministic and probabilistic designs have been developed to overcome the uncertainties in analysis and design. Deterministic design aims to simplify the problem by incorporating an experimental safety factor. In fact, a guaranteed design in the context of a deterministic design approach implies to consider a high safety factor which causes an overdesign of the system and high cost. The most important difference between probabilistic and deterministic design is that in probabilistic design, in contrast with deterministic design, the uncertainty in exploring the structure's behavior is explicitly considered (Ditlevsen and Madsen, 2005).

Reliability is often identified with its complements, while, the probability of failure (P_f), means that a structure will not function as expected. In other words, the analysis of a structure's reliability is the assessment of the structure's failure probability by determining whether the limit state functions exceed the allowable limit or not (Shayanfar et al., 2015).

To estimate the P_f, the Monte Carlo technique has been widely applied in many engineering problems; such as building industry, aircraft manufacturing, shipbuilding, etc. (Jiang et al., 2013; Kartal et al., 2011). This method was introduced by Metropolis and Ulam (1949). Although first and second-order reliability methods offer approximate solutions for issues involving nonlinear boundary conditions, abnormal random variables, and multiple design points, the Monte Carlo method, in contrast, has been noted to provide straightforward estimations of the accurate failure probability (Melchers, 2018). In this method, it has been shown that random samples are generated for each variable according to the probability density function of the variable and by placing the samples in the limit state function, the structure's failure probability is calculated (Nowak and Collins, 2012; Sorensen, 2004; Zhang et al., 2014). This probability is defined by the ratio of the number of points in the failure zone to the total number of points generated based on the variable density function (Sorensen, 2004; Zhang et al., 2014).

The integration of reliability into the design process of agricultural machinery presents a novel approach to address the limitations of traditional (classic) designs and achieve an optimal and more dependable design (Kharmnda et al., 2014). The probabilistic design approach has found widespread application in various industrial sectors, and its application in the agricultural machinery domain is relatively new. However, these approaches, except for one or two cases (Abo Al-Kheer et al., 2011), have received less attention for the design of tillage machines.

Abo Al-Kheer et al. (2011), developed a reliability-based design approach for the first time using randomly combining tillage forces to achieve a reliable tillage machine. To accomplish this objective, two validation techniques including Monte Carlo simulation (MCS) and first-order reliability methods were employed. These methods were applied to determine the design standard for a chisel plow. The findings demonstrated that the chisel plow design standard exhibited a high level of reliability. However, to attain an optimal design solution from an economic standpoint, a reliability-based design approach was utilized to minimize the volume of the chisel plow structure. As a result, the initial volume of the standard structure was reduced by 6.86%. During a study conducted by Abo Al-Kheer et al. (2011), it was concluded that incorporating economic constraints into the reliability-based design approach can result in an optimal design of tillage tools, ensuring the desired reliability level at a reduced cost.

Kharmnda et al. (2014) optimized the design of the chisel plow standard based on the reliability analysis using the Optimal Safety Coefficient (OSF) approach, which included uncertainty in the tillage forces. The tillage forces were calculated according to McKyes and Ali's analytical model (1977) with a number of modifications that comprised of the effect of soil-metal adhesion and tool speed. The OSF algorithm was conducted in three main steps: 1- determining the design point, 2- calculating the safety factor and 3- calculating the optimal solution. The OSF approach was expanded to encompass various nonlinear probability distributions, including the lognormal, uniform, Weibull, and Gumbel probability distribution functions. Furthermore, the probability density function (PDF) of the horizontal force acting on the chisel plow standard was derived. The outcomes revealed that incorporating reliability-based design principles can yield dependable structures with reduced costs (Kharmnda et al., 2014).

The interaction between tillage machines, tools, and soil is a complex process where the design parameters and variables are inherently random. As a result, reliability can be effectively applied in the design and construction of tillage machines and tools. However, by reviewing the available literature, it is evident that there is a scarcity of scientific studies specifically addressing the design and analysis of plow chassis based on reliability. To the best of our knowledge, no research has been conducted thus far that focuses on the reliability analysis of a mounted moldboard plow chassis. Therefore, this study aimed to apply the Monte Carlo simulation method to analyze the reliability of the chassis of a mounted moldboard plow as a statically indeterminate asymmetric structure. Using this method, the P_f and β for different parts of a moldboard plow structure including the crossbar, mast, brace, longitudinal toolbar, lateral toolbar, side toolbar, and bottom standard were calculated and analyzed.

MATERIALS and METHODS

In this study, a 3D- finite element method (3D- FEM) model of the interaction of a three-bottom mounted moldboard plow and soil developed by Nazemosadat et al. (2022a) was employed. Fig. 1 shows the 3D-FEM model of the plow (P12-3, GAK Co., Mashhad, Iran) and its components with the actual dimensions of the plow (Table 1) in Solid Work 2016 software as have been already reported by Nazemosadat et al. (2022b).

Fig. 2 shows a 3D model of FEM plow-soil interaction using Abaqus software as reported by Nazemosadat et al. (2022a). Abaqus software is a powerful finite element analysis (FEA) software. It is widely used in various industries and academic institutions for simulating and analyzing the behavior of structures, components, and materials under different physical conditions. Abaqus offers a comprehensive range of capabilities for performing both linear and nonlinear analyses, allowing users to accurately model and predict the response of complex engineering systems.

In this model, a soil box with dimensions of 3.5 × 2.5 × 1 m (i.e. length × width × height) was employed. The moldboard plow was represented as a rigid body to analyze the forces exerted on its structure. The soil's mechanical behavior was defined as elastic-perfectly plastic, adopting a linear Drucker-Prager yield function (Nazemosadat et al., 2022a). Following the estimation of forces acting on the plow under various soil conditions, the plow components made of CK45 and ST52 steel were included in the chassis static analysis. The structural analysis considered the deformable nature of the plow. The moldboard plow frame material characteristics have been already reported in accordance with Table 2 (Nazemosadat et al., 2022a).

ST52 is a designation for a low alloy, high tensile strength structural steel. It is a commonly used grade in the construction of machinery, equipment, and structural components. ST52 steel typically contains carbon, manganese, silicon, phosphorus, sulfur, and small amounts of other alloying elements to enhance its mechanical properties. It is known for its excellent strength, toughness, and weldability, making it suitable for applications that require high load-bearing capacity and resistance to impact and vibrations. CK45 is a designation for a medium-carbon steel alloy. It is a widely used grade for various industrial applications, including machinery parts, shafts, axles, hydraulic cylinders, and general engineering components. CK45 steel contains carbon, manganese, and small amounts of other alloying elements such as silicon, chromium, and nickel. It offers good strength, hardness, and wear resistance, making it suitable for applications that require high strength and durability. The general contact between soil and parts involved tillage tool surfaces was defined using tangential behavior with a coefficient of friction of 0.35 (Nazemosadat et al., 2022a).

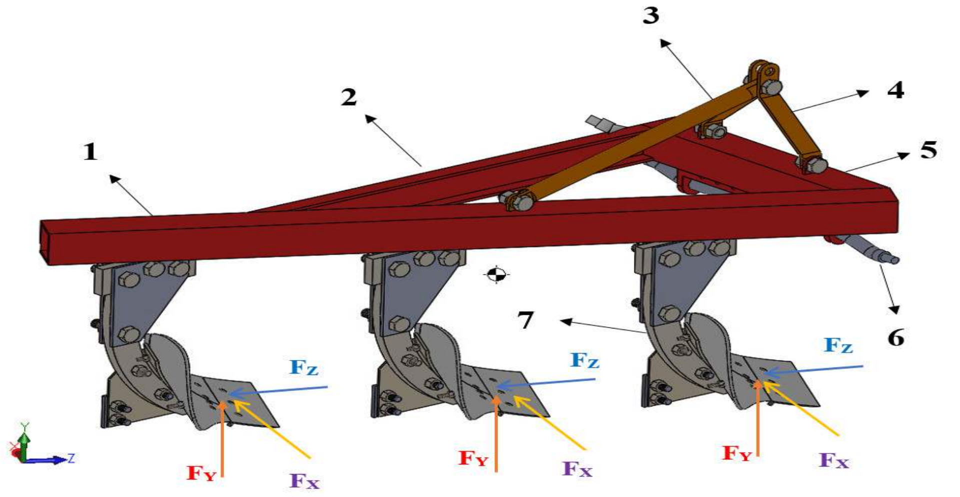

Fig. 1. A 3D model of the moldboard plow in Solid Work 2016 software and forces applied from soil to each bottom, 1= longitudinal toolbar, 2= side toolbar, 3= brace, 4= mast, 5= lateral toolbar, 6= crossbar, 7= bottom standard, F_X= lateral force, F_Y= vertical force, F_Z= longitudinal force (Retrieved from Nazemosadat et al., 2022b).

Table 1. Technical specifications of various parts of the moldboard plow (Retrieved from Nazemosadat et al., 2022a).

Part name	Specification	Material*	Dimension (m)	Weight (kg)
Longitudinal toolbar	Square tubes 120×120×10 mm	ST52	2.16	68.69
Lateral toolbar	Square tubes 120×120×10 mm	ST52	0.85	27.03
Side toolbar	U profile 120×60×8 mm	ST52	1.32	15.97
Mast	Belt* 65×10 mm	ST52	1.12	5.71
Brace	tube D=40, t=3 mm	ST52	0.96	3.28
Crossbar	rod D=60	ST52	0.69	15.32
Standards (3 pcs.) and fittings	belt 100×30 mm	CK45*	1.8	42.48
	belt 300×30 mm		0.3	21.21
	belt 240×10 mm		1.4	26.32
Bottom (moldboard, heel, landside, and share) (3 pcs.)	-	CK45	0.96×0.33×0.42	155.06
	Total weight of the moldboard plow:			381.07

* ST52 and CK45 are both designations for specific types of steel alloys used in engineering and manufacturing applications.

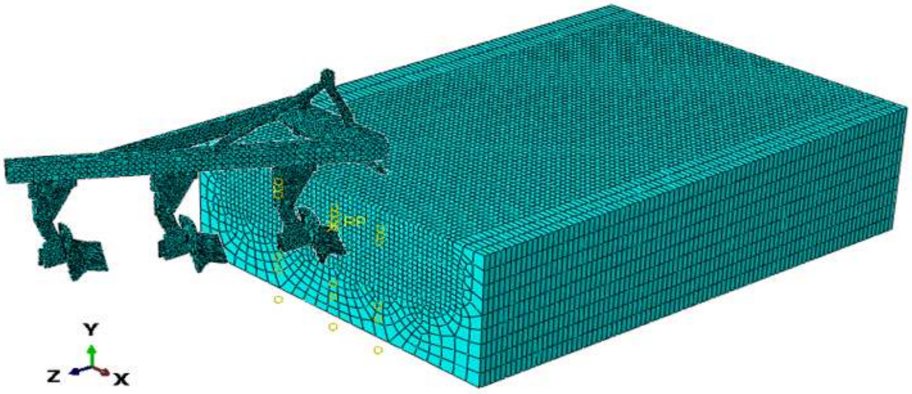

Fig. 2. Finite element mesh of the soil box and moldboard plow at a plowing depth (d) of 30 cm (Retrieved from Nazemosadat et al., 2022a).

Table 2. Characteristics of the moldboard plow frame materials used in the finite element method (FEM) model (Retrieved from Nazemosadat et al., 2022a).

Material	Density (kg/m^3)	Elastic modulus (MPa)	Poisson's ratio	Yield stress (MPa)
CK45*	7830	2.06×10^5	0.3	414
ST52*	7850	2.1×10^5	0.3	360

* CK45 and ST52 are both designations for specific types of steel alloys used in engineering and manufacturing applications.

To mesh the moldboard plow and soil, the C3D10 (i.e. 10-node tetrahedral element) and C3D8R (i.e. 8-node linear brick continuum element) elements were utilized, respectively (Nazemosadat et al., 2022a). The plow-soil interaction analysis focused on extracting longitudinal (F_Z), lateral (F_X), and vertical (F_Y) forces acting on the plow under the most critical conditions, specifically at a depth of 0.30 m and a velocity of 3 m s^{-1}, considering highly compacted soil properties. In the static analysis, the forces obtained from the plow-soil interaction were applied to the plow, allowing for the determination of stress distribution across different components of the plow chassis.

The predictions of the soil-moldboard plow FEM model of the draft (longitudinal) force under different soil conditions agreed well with the model of Godwin et al. (2007) as discussed by Nazemosadat et al. (2022a).

The Monte Carlo simulation (MCS)

The MCS method is recognized as a statistical technique that involves simple random sampling or statistical testing to identify random variables using randomly generated sample sets. This method serves as a valuable mathematical tool for estimating the approximate probability of a specific event that arises from a series of stochastic processes (Shayanfar et al., 2015). In this method, the analysis process includes the following steps:

1. Selecting the type of probability distribution function of the random variables and its parameters.
2. Simulation of random variables according to the probability distribution function and related parameters.
3. Placing the numerical values of each variable in the limit state function.
4. Determining the P_f according to the number of simulations in the failure space to the total number of simulations.

Determining the random variables

As mentioned earlier, the structure and working conditions of the tillage machines and tools are due to direct interaction with the soil in a way that the parameters and variables affecting their design are clearly and inherently random. Therefore (according to the simulation conditions in Abaqus), first some important soil properties such as density (ρ), Young's modulus (E_s), compressive yield stress (σ_c), internal Drucker-Prager angle of friction (ξ) and plowing depth (d) and speed (v) were considered random variables affecting the longitudinal (Fz), lateral (Fx) and vertical (Fy) forces applied to the plow by the soil. It should be noted that in the reliability analysis of the plow structure, Fz, Fx and Fy forces are considered as the random variables that depend on the soil's properties, plowing depth and plowing speed. Regarding the characteristics of the plow chassis, Young's modulus (E_m), was taken as an effective random variable in calculating the maximum Von-Mises stress (σ_V) of the chassis.

Selecting the type of probability distribution for the random variable

To determine the most suitable distribution for the random variables, the data associated with these variables were analyzed using EasyFit software. Eight different distribution functions, namely uniform, Frechet, exponential, beta, normal, lognormal, Weibull, and Rayleigh distribution functions, were considered for each random variable. The data distribution function and histogram were extracted for each variable, and a Chi-square comparison was conducted to evaluate and select the best probability distribution. The Chi-square test was employed to assess the compatibility between the probability distribution function and the frequency histogram of the data. Equation 1 [Eq. (1)] shows how this experiment works.

$$x^2 = \frac{\sum(n_i - e_i)^2}{e_i} \qquad \text{Eq. (1)}$$

In this equation, the term x^2 represents the error rate associated with each distribution function. It is used to compare the differences between the function and the data histogram, with a lower value indicating a closer fit (Sorensen, 2004). The variables n_i and e_i correspond to the function value and observed value, respectively. The distribution function that yields the least difference with the data histogram is assigned the rank of one.

Based on various studies on structural reliability analysis (Abo Al-kheer et al., 2011; Mojahed and Ahmadi Nedushan, 2013; Kharmnda et al., 2014), it has been found that the normal distribution and lognormal distribution are commonly used as the most suitable distributions. In the case of the normal distribution, also known as the Gaussian distribution, the probability density function (PDF) value can be determined using Eq. (2) as follows:

$$PDF = f_x(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \qquad \text{Eq. (2)}$$

where x represents the random variable, μ is the mean, and σ signifies the standard deviation, the value of the cumulative distribution function (CDF) can be obtained using Eq. (3) as follows:

$$CDF = F(\mathrm{x}) = \int_{-\infty}^{\mathrm{x}} \mathrm{f_x(x)dx} = \int_{-\infty}^{\mathrm{x}} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\mathrm{x}-\mu}{\sigma}\right)^2\right] \mathrm{dx} \qquad \text{Eq. (3)}$$

where the variable x has a lognormal distribution with the mean of μ', and standard deviation (σ') as defined by Eqs. (4) and (5), respectively.

$$\mu' = \exp\left(\mu + \frac{\sigma^2}{2}\right) \qquad \text{Eq. (4)}$$

$$\sigma'^2 = (\exp\sigma^2 - 1)\exp(2\mu + \sigma^2) \qquad \text{Eq. (5)}$$

In the case of the lognormal distribution, the probability density function (PDF) value can be obtained using Eq. (6):

$$PDF = f_x(x) = \frac{1}{x\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{Lnx - \mu}{\sigma}\right)^2\right] \qquad \text{Eq. (6)}$$

Furthermore, in this distribution the value of the CDF is equal to:

$$CDF = F(\mathrm{x}) = \int_{-\infty}^{\mathrm{x}} \mathrm{f_x(x)dx} = \int_{-\infty}^{\mathrm{x}} \frac{1}{\mathrm{x}\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\mathrm{Lnx}-\mu}{\sigma}\right)^2\right] \mathrm{dx} \qquad \text{Eq. (7)}$$

Generation of a sample set of probability distributions

At this stage, according to the conditions such as the duration of analysis and simulation process in Abaqus (Each analysis takes time), 100, 200 and 300 samples of the soil properties' random numbers were generated as the random variables with normal distribution in order to simulate the Monte Carlo method. These variables consisted of soil density (ρ), Young's modulus (E_s), compressive yield stress (σ_c), internal Drucker-Prager angle of friction (ξ), plowing depth (d) and speed (v).

Calculation of statistical characteristics of the random variables

According to the distribution type selected for random variables, the standard deviation value, the mean and the variation coefficient of the random variables were measured.

The simulation of random variables and the placement of each variable's numerical values in the limit state function

Random variables of the soil properties as well as different plowing depths and velocities were entered into Abaqus software and 100, 200 and 300 simulations (dynamic analysis) were performed, which resulted in production of longitudinal (Fz), lateral (Fx) and vertical (Fy) forces. In the next step, according to the forces obtained from dynamic simulation and their application on the plow in Abaqus software, as well as applying the random variables of Young's modulus (E_m) of the chassis, 100, 200 and 300 static analyses were accomplished corresponding to the random variables. In each analysis, Von-Mises stress (σ_v) applied to the chassis were considered as the output of the analysis. It should be noted that the standard deviation of the variables was considered equal with 0.04 of its average in random variables' production of chassis' Young's modulus (E_m) (Hadianfard et al., 2018).

Probability of failure (P_f) calculation

The reliability relationship is established by considering two crucial parameters including the strength and the loads acting on the structure. The P_f function, which represents the probability of failure, can be expressed using Eq. (8):

$$g(R, Q) = R - Q \qquad \text{Eq. (8)}$$

In Eq. (8), the function $g(R, Q)$ represents the limit state function of the load and resistance of the structure. Within this equation, both the resistance (R) and load (Q) functions consist of multiple random variables with varying probability distribution functions, which are influenced by factors such as the nature of dimensions, the type of structural materials, and the applied loads. The region of structural failure is determined based on the limit state function (g), which describes the relationship between resistance and load. Consequently, the structural P_f can be calculated using Eq. (9) as presented by Nowak and Collins (2012):

$$P_f = P\left[\mathrm{g(R - Q)} \leq 0\right] = \int_{\mathrm{g(R-Q)}\leq 0} \mathrm{f_X}(X) d_X \qquad \text{Eq. (9)}$$

This integral signifies the area under the probability distribution function of the base random variables ($f_X(X)$) up to the failure limit $R - Q \leq 0$. This value represents the probability of failure (P_f) for the structure. The probability of failure (P_f) is the opposite of the reliability index (β). The higher β would result in a lower P_f.

After doing the simulation process in Abaqus software, the maximum Von-Mises stress (σ_v) variables for different parts of the moldboard plow chassis including the crossbar, mast, brace, longitudinal toolbar, lateral toolbar, side toolbar and bottom standard were obtained and the value of the limit state function was calculated via Eq. (10):

$$g(\mathrm{x}) = \sigma_y - \sigma_{max} \qquad \text{Eq. (10)}$$

where σ_y is the yield stress and σ_{max} is the maximum Von-Mises stress of the plow chassis. The $g(\mathrm{x}) < 0$ means that the maximum Von-Mises stress is greater than the yield stress of the plow structure ($\sigma_{max} > \sigma_y$). In other words, the structure's resistance is decreased due to the defined loads and characteristics, which leads to the plow structure's failure. Therefore, one unit is added to the number of structural failure times (N_F), which its initial value is zero. These calculations are repeated N times and the P_f is measured as Eq. (11):

$$P_f = \frac{N_F}{N} \qquad \text{Eq. (11)}$$

where N_F is the number of times that the structure fails and N is the number of repetitions or samples. In this study, N was equal to 100, 200 and 300. It should be mentioned that the plow structure's P_f was calculated for each part separately. The coefficient of variation (COV) of chassis yield stress (σ_y) was considered 0.08 as shown by Hadianfard et al., (2018).

Calculation of the reliability index (β)

The β is defined by Eq. (12) based on the mean values and standard deviation of the limit state function:

$$\beta = \frac{\mu_g}{\sigma_g} = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R{}^2 + \sigma_Q{}^2 - 2\rho_{RQ}\sigma_R\sigma_Q}} \qquad \text{Eq. (12)}$$

In this equation, μ_g and σ_g are the mean and standard deviation of the limit state function, respectively. The μ_R is the mean resistance function, μ_Q is the mean load function, $\rho_{RQ}$is the correlation coefficient between the two random variables' load and resistance, σ_R is the standard deviation of the resistance function and σ_Q is the standard deviation of the load function.

For a particular resistance and loading state with normal and independent probability distribution function, the limit state function is normal; so, the failure density function is expressed by Eq. (13):

$$f_g(g) = \frac{1}{\sigma_g\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{g-\mu_g}{\sigma_g}\right)^2\right] \qquad \text{Eq. (13)}$$

when $g = 0$ is normally distributed, the P_f of Eq. (14) is calculated by placing $g = 0$ in Eq. (13) as discussed by Shayanfar et al., (2015):

$$\begin{aligned} P_f &= \int_{-\infty}^{0} \frac{1}{\sigma_g\sqrt{2\pi}}\, exp\left[-\frac{1}{2}\left(\frac{0-\mu_g}{\sigma_g}\right)^2\right] dg \\ &= \int_{-\infty}^{0} \frac{1}{\sigma_g\sqrt{2\pi}}\, exp\left[-\frac{1}{2}\beta^2\right] dg \\ &= 1 - \Phi(\beta) = \Phi(-\beta) \end{aligned} \qquad \text{Eq. (14)}$$

In this equation, β is the reliability index and Φ is the standard normal cumulative distribution function (Nowak and Collins, 2012). Solving the above integral in n-dimensional space with abnormal random variables is very difficult and therefore to determine the P_f various methods were used including first-order second-moment method, first-order reliability and methods based on the MCS.

After calculating the failure probability of different parts of the moldboard plow chassis, the β reliability index was measured through Eq. (15) as follows:

$$\beta = -\Phi^{-1}(p_f) \qquad \text{Eq. (15)}$$

The structural system's reliability

Many structural systems are composed of structural elements; consequently, it is essential to distinguish between the reliability of each structural element and the reliability of the whole system (Shayanfar et al., 2015). To assess the reliability, the structural systems were classified into three categories including series, parallel and mixed (the combination of series and parallel) categories. Due to the direct interaction of the plow with the soil, and in order to analyze the reliability of the operating conditions' structure of the mounted moldboard plow, the plow structure should be considered as a series system. A series system is sometimes referred to as the weakest interface system because the failure of this system is associated with the failure of the weakest element of the system. The P_f of a series system consisting of n elements is obtained from Eq. (16):

$$\begin{aligned} P_f &= F_R(q) = P(R \le q) = 1 - P(R > q) \\ &= 1 - P[(R_1 > q_1) \cap (R_2 > q_2)] \cap \ldots \cap (R_n > q_n) \\ &= 1 - P[(R_1 > q_1)(R_2 > q_2)](R_n > q_n) \end{aligned} \qquad \text{Eq. (16)}$$

$$= 1 - \prod_{i=1}^{n}\left[1 - F_{R_i}(q_i)\right] = 1 - \prod_{i=1}^{n}\left[1 - P_{f_i}\right]$$

Where R is the total resistance of the system, Q is the load on the system, R_i is the resistance of the i element (part), Q_i is the load on the i element, and $F_R(Q)$ is a function of the cumulative distribution of the system resistance.

In order to evaluate the reliability of the moldboard plow structure, first the P_f of each element of the plow structure including the crossbar, mast, brace, longitudinal toolbar, lateral toolbar, Side toolbar, and the bottom standard was calculated, then the β of the structural system was measured using the Eq. (15).

RESULTS and DISCUSSION

The Monte Carlo simulation

Random variables and probability distributions

In order to select the best probability distribution for random variables of soil and plow chassis, EasyFit software was used. Eight distribution functions including uniform, frechet, exponential, beta, normal, lognormal, Weibull, and Rayleigh distribution functions were selected for the random variable of the compressive yield stress (σ_c) and were compared using the Chi-squared test. The distributions were ranked from one to eight accordingly. The analysis revealed that rank one corresponded to the normal probability distribution, while rank eight was associated with the exponential distribution. Consequently, the normal probability distribution was identified as the most suitable distribution for the random variable of the soil's compressive yield stress (σ_c). Similarly, the chi-score test was conducted for other variables and the best type of distribution for the random variables related to other soil properties, plowing speed, and Young's modulus (E_m) of the chassis, normal distribution was obtained. For random variables including longitudinal (Fz), lateral (Fx), and vertical (Fy) forces, lognormal distribution was considered.

The probability and statistical characteristics of random variables

Table 3 represents the probability characteristics of the randomly selected soil variables as well as the random variables of plowing depth and speed. Based on the chosen normal probability distribution, the mean and standard deviation of the random variables were determined. According to Table 3, the highest standard deviation is related to the compressive yield stress of the soil, which shows the significant dispersion of the data of this variable compared to other random variables of the soil.

Tables 4 and 5 also display the probability properties and statistical characteristics of the random variables related to the plow chassis. Among the variables of longitudinal (Fz), lateral (Fx), and vertical (Fy) forces according to Tables 4 and 5, respectively, the highest standard deviation and coefficient of variation are related to the random variable Fy.

The simulation of random variables

Some of the random variables' simulation data of the soil properties are illustrated in Table 6 obtained by placing different numerical values of each variable in Abaqus software. Also, some of the random variables' simulation data of plow chassis characteristics are exhibited in Table 7. These data included Young's modulus (E_m) and longitudinal (Fz), lateral (Fx), and vertical (Fy) forces data which are obtained by placing different numerical values of each variable in Abaqus software.

Figs. 3, 4, and 5 show an example of the Monte Carlo simulation results in terms of the stress of each part of the plow structure and the yield stress. In these diagrams, the green, red, and gray circles represent the areas of health, failure, and limit state functions, respectively.

According to Fig. 3, with respect to the value of the limit state function $g(\mathrm{x}) = \sigma_y - \sigma_{max}$, the Monte Carlo simulation results showed that all stress variables are located in the failure region (red circles), So the failure probability of the crossbar was very high. However, according to Fig. 4, all stress variables are located in the health region (green circles), so the longitudinal toolbar was reliable under the applied loads, and the P_f was zero.

Based on the information presented in Fig. 5, it can be observed that the number of stress variables falling within the healthy region (green circles) is higher compared to the number of stress variables within the failure region (red circles). This suggests that the failure probability of the brace is relatively low.

Calculation of failure probability (P_f) and reliability index (β)

Based on Table 8, after simulation implementing process in Abaqus and the extraction of Von-Mises stress (σ_v) variables, according to the value of the limit state function $g(\mathrm{x}) = \sigma_y - \sigma_{max}$ and also the amount of stress on the plow chassis yield, different parts' failure probability (P_f) of the plow chassis was calculated. Additionally, Table 8 shows that along with increasing the number of simulations, the P_f is decreased in the brace, mast, and bottom standard and as a result, the β is increased in these parts. In addition, according to the data of Table 8, the crossbar has the highest failure probability and the toolbars have the lowest failure.

Table 3. Probability characteristics of the soil random variables.

Random variables	Unit	Type of distribution	Distribution parameters
Density, ρ	g cm^{-3}	Normal	$\sigma = 0.1$, $\mu = 1.9$
Young's modulus, E_s	MPa	Normal	$\sigma = 0.15$, $\mu = 7.5$
Internal Drucker-Prager angle of friction, ξ	degree	Normal	$\sigma = 2.27$, $\mu = 50$
Compressive yield stress, σ_c	kPa	Normal	$\sigma = 3.84$, $\mu = 145$
Plowing depth, d	cm	Normal	$\sigma = 1.8$, $\mu = 30$
Plowing speed, v	m s^{-1}	Normal	$\sigma = 0.1$, $\mu = 3$

Table 4. Probability characteristics of the plow chassis random variables.

Random variables	Unit	Type of distribution	Distribution parameters
Bottom lateral force, Fx	kN	Lognormal	$\sigma = 0.123$, $\mu = 1.023$
Bottom vertical force, Fy	kN	Lognormal	$\sigma = 0.141$, $\mu = 0.80$
Bottom longitudinal force, Fz	kN	Lognormal	$\sigma = 0.085$, $\mu = 3.053$
Young's modulus, E_m	MPa	Normal	$\sigma = 8273.7$, $\mu = 2.093 \times 10^5$

Table 5. Statistical characteristics of plow chassis random variables.

Random variables	mean	Variance	Range	Coefficient of variation
Bottom lateral force, Fx	2.803	0.116	1.786	0.121
Bottom vertical force, Fy	2.248	0.099	1.543	0.140
Bottom longitudinal force, Fz	21.262	3.304	9.969	0.085
Young's modulus, E_m	2.09×10^5	6.84×10^7	37064	0.039

Table 6. Some of the data of lateral, vertical, and longitudinal forces on the plow obtained from the Abaqus analysis based on 300 simulations of the random variables including plowing speed, plowing depth, soil density, soil Young's modulus, compressive yield stress, and internal Drucker-Prager angle of friction, stages of the reliability analysis confidence using the Monte Carlo method at the highest depth and speed of the progress.

No of Row	plowing depth (cm)	plowing speed (m s^{-1})	soil density (g cm$^{-3)}$	soil Young's modulus (MPa)	compressive yield stress (kPa)	internal Drucker-Prager angle of friction (degree)	plow lateral force (kN)	plow vertical force (kN)	plow longitudinal force (kN)
1	30.25750	3.03280	2.06945	6.72386	149.26230	44.00880	8.571	6.051	60.920
2	28.79130	2.99380	1.75792	6.68146	147.81275	45.68145	10.764	9.419	80.569
3	28.85820	2.97000	1.82794	6.01154	145.83240	46.08452	9.278	7.283	60.039
4	28.98660	2.97610	1.87246	6.85859	157.80703	45.49510	7.578	6.670	64.645
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
149	29.15860	3.08800	1.88908	6.84578	145.42088	45.64883	7.986	5.576	63.835
150	29.06110	3.10550	1.85038	6.52519	145.03123	44.20019	7.093	6.345	61.316
151	30.98110	2.82580	1.84026	6.35309	147.89878	46.55545	8.699	6.555	69.422
152	30.62720	3.02170	1.97726	6.53815	143.45892	41.54977	9.742	6.529	69.271
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
297	28.76880	3.08030	1.71025	6.66253	146.36039	47.66099	7.287	6.971	62.958
298	30.91340	2.93070	2.03130	6.44456	147.46987	45.70217	7.816	5.896	63.699
299	31.48850	2.95990	1.99335	6.48342	147.84056	42.47571	8.600	7.232	67.490
300	30.45750	3.02576	1.91603	6.58049	146.58089	41.04441	8.421	6.174	61.330

Table 7. Some of the data of of plow chassis analysis using Abaqus software in 300 times random variables' simulation of longitudinal forces (Fz), lateral (Fx) and vertical (Fy) of the Monte Carlo reliability analysis stages at the highest depth and speed of the progress.

No Of Row	Maximum Von-Mises stress on the crossbar (MPa)	Maximum Von-Mises stress on the bottom standard (MPa)	Maximum Von-Mises stress on the mast (MPa)	Maximum Von-Mises stress on the brace (MPa)	Maximum Von-Mises stress on the longitudinal toolbar (MPa)	Maximum Von-Mises stress on the lateral toolbar (MPa)	Maximum Von-Mises stress on the side toolbar (MPa)
1	1.034×10^{3}	348.160	327.678	342.820	244.760	188.200	170.622
2	9.581×10^{2}	329.944	315.002	325.363	234.134	181.725	165.438
3	9.308×10^{2}	323.392	310.443	319.084	230.312	179.397	163.573
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
149	9.799×10^{2}	335.176	318.643	339.830	237.186	187.091	169.734
150	1.110×10^{3}	366.400	340.370	330.377	255.400	183.585	166.927
151	1.106×10^{3}	365.440	339.702	360.300	254.840	194.683	175.813
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
298	1.019×10^{3}	344.560	325.173	339.370	242.660	186.920	169.597
299	1.077×10^{3}	358.480	334.859	352.710	250.780	191.868	173.559
300	9.789×10^{2}	334.936	318.476	330.147	237.046	183.500	166/858

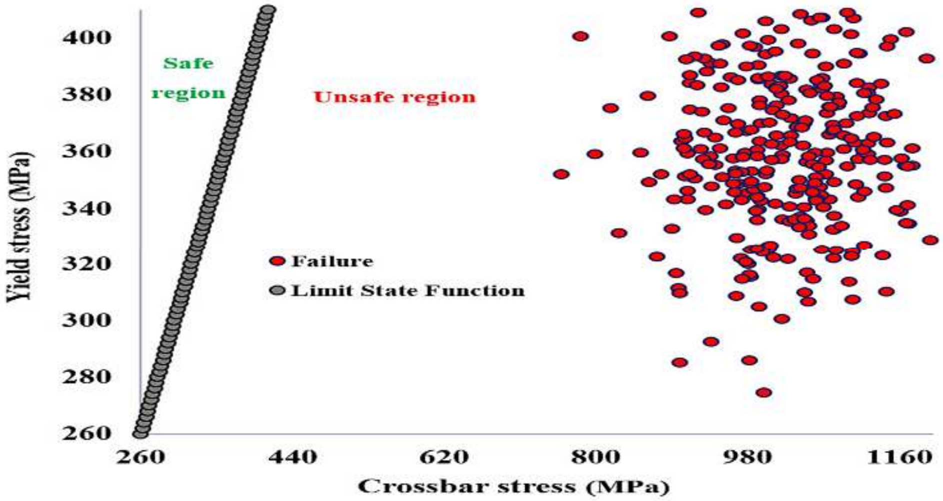

Fig. 3. The results of the Monte Carlo simulation in terms of crossbar stress and yield stress.

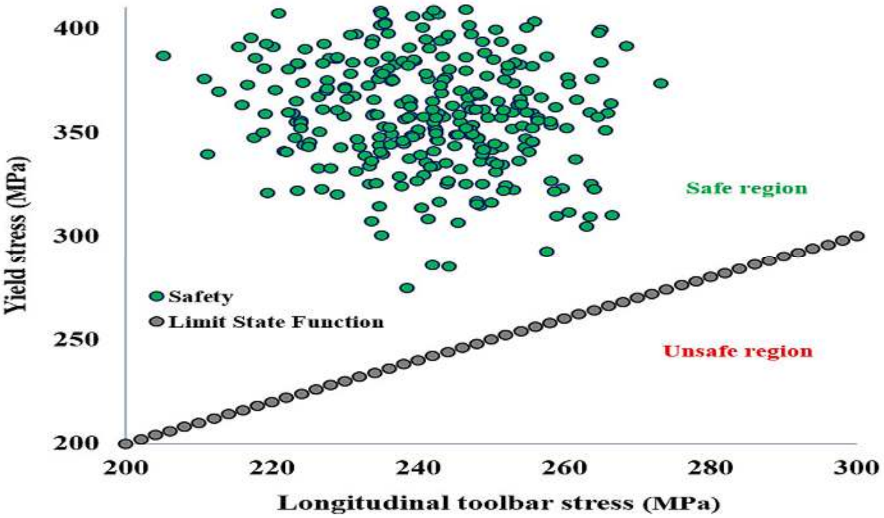

Fig. 4. The results of the Monte Carlo simulation in terms of longitudinal toolbar stress and yield stress.

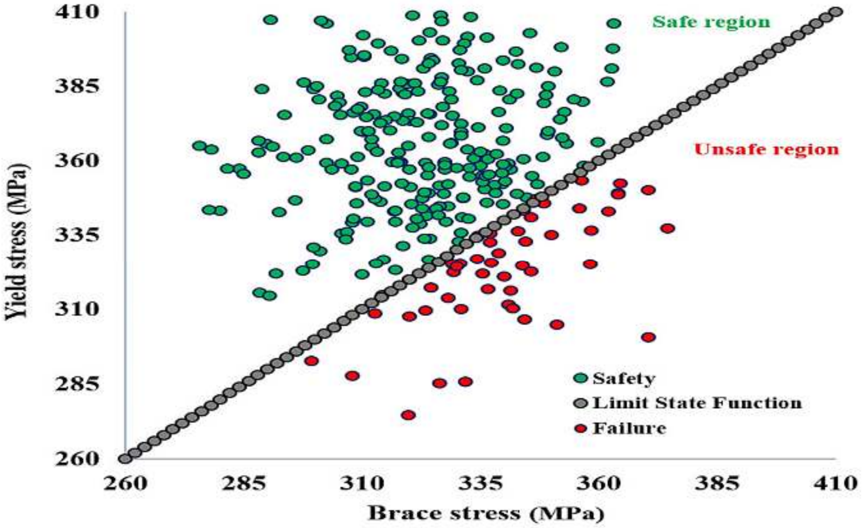

Fig. 5. The results of the Monte Carlo simulation in terms of brace stress and yield stress.

Table 8. The probability of failure (P_f) and reliability index (β) data of different parts of plow chassis in different simulations.

part	index	Number of simulations		
		100	200	300
Longitudinal toolbar	P_f	0	0	0
	β	6.09	6.24	6.77
Lateral toolbar	P_f	0	0	0
	β	7.21	6.95	7.43
Side toolbar	P_f	0	0	0
	β	7.78	8.01	8.32
Mast	P_f	40×10^{-3}	35×10^{-3}	33.3×10^{-3}
	β	1.8730	1.9098	1.9223
Brace	P_f	190×10^{-3}	175×10^{-3}	165×10^{-3}
	β	0.9081	0.9521	0.9814
Crossbar	P_f	1	1	1
	β	-7.08	-6.95	-6.27
Standard (Nazemosadat et al., 2022b)	P_f	310×10^{-3}	304×10^{-3}	296×10^{-3}
	β	0.5566	0.5742	0.5976

Calculation of the plow structure system's reliability

According to Table 8, after calculating the P_f of moldboard plow structural parts, the reliability of the plow structure system was evaluated for 300 Monte Carlo simulations based on Eq. (16). The probability of failure system was achieved equal to P_f=1. According to this value, it can be concluded that in general, the plow set at a critical speed of 3 $\mathrm{m\,s^{-1}}$ and plowing depth of 30 cm in very compacted soil is unreliable; therefore, strengthening the plow's weak parts are compulsory.

CONCLUSIONS

In this study, the reliability analysis of different parts of a three-bottom mounted moldboard plow structure was performed using the Monte Carlo simulation method. The results of the analysis revealed that the crossbar had the highest failure probability while the toolbars had the lowest failure probability. Also, the bottom standard, braces, and masts had a low-reliability index (β) and therefore needed reinforcement to work safely in very compacted soils. Calculation of system failure probability (P_f) also showed that the whole set of plow structures was not reliable in very compacted soil conditions and in general, this structure should be strengthened in some parts. Besides, the data of the β of the parts such as longitudinal, lateral, and side toolbars displayed that because of the high reliability obtained in these parts, their optimization could reduce the weight and cost of these parts.

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Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFRENCES

Abo Al-kheer, A., El-Hami. A., Kharmanda, M. G., & Mouazen, A. M. (2011). Reliability-based design for soil tillage machines. *Journal of Terramechanics*, 48(1), 57–64. https://doi.org/10.1016/j.jterra.2010.06.001.

Ditlevsen, O., & Madsen, H. O. (2005). *Structural reliability methods*. Internet edition. 2.2.5. First edition published by John Wiley & Sons, Chichester, 1996. https://www.ukm.my/kamal3/rro/note%20Structural%20Reliability%20Methods.pdf

Godwin, R. J., O'Dogherty, M. J., Saunders, C., & Balafoutis, A. T. (2007). A force prediction model for moldboard plows incorporating the effects of soil characteristic properties, plow geometric factors and plowing speed. *Biosystems Engineering*, 97(1), 117-129. https://doi.org/10.1016/j.biosystemseng.2007.02.001

Hadianfard, M. A., Malekpour, S., & Momeni, M. (2018). Reliability analysis of H-section steel columns under blast loading. *Journal of Structural Safety*, 75, 45–56. https://doi.org/10.1016/j.strusafe.2018.06.001.

Jiang, S., Du, C., & Hong, Y. (2013). Failure analysis of a cracked concrete gravity dam under earthquake. *Engineering Failure Analysis*, 33, 265-280. https:// doi: 10.1016/j.engfailanal .2013.05.024

Kartal, M. E., Başağa, H. B. & Bayraktar A. (2011). Probabilistic nonlinear analysis of CFR dams by MCS using Response Surface Method. *Applied Mathematical Modelling*, 35(6), 2752-2770. https://doi: 10.1016/j.apm. 2010.12.003.

Kharmnda, G., Ibrahim, M. H., Abo Al-Kheer, A., Guerin, F., & El-Hami, A. (2014). Reliability-based design optimization of shank chisel plow using optimum safety factor strategy. *Computers and*

Electronics in Agriculture, 109, 162-171. https://doi: org/10.1016/j.compag.2014.09.001.

McKyes, E & Ali, O. S. (1977). The cutting of soil by narrow blades. *Journal of Terramechanics*, 14, 43-58. https://doi.org/10.1016/0022-4898(77)90001-5

Metropolis, N., & Ulam, S. (1949). The Monte Carlo Method. *Journal of American Statistical Association*, 44, 335-41. https://doi: 10.1080/01621459.1949. 10483310.

Melchers, R. E. (2018). *Structural reliability analysis and prediction*. Chichester: John Wiley & Sons. doi:10.1002/978111926610

Mojahed, M. M., & Ahmadi Nedushan, B. (2013). Reliability analysis of steel frames based on advanced methods of Monte Carlo. 7th National Congress of Civil Engineering. Shahid Nikbakht Faculty of Engineering. 17 and 18 May. Sistan and Baluchestan University. Zahedan. (In Persian).

Nazemosadat, S. M. R., Ghanbarian, D., Naderi-Boldaji, M., & Nematollahi, M. A. (2022a). Structural analysis of a mounted moldboard plow using finite element simulation method. *Spanish Journal of Agricultural Research*. 20(2), 1-14. https://doi.org/10.5424/sjar/2022202-18157.

Nazemosadat, S. M. R., Naderi-Boldaji, M., Ghanbarian, D., & Nematollahi, M. A. (2022b). Reliability analysis of a mounted moldboard plow bottom standard using the FORM method. *Journal of Optimization in Industrial Engineering.* 15(2), 170-190. https://doi.org/10.22094/joie.2022.1932748.1868.

Nowak, A. S., & Collins, K. R. (2012). *Reliability of Structures*. Second Edition. CRC Press. https://www.routledge.com/Reliability-of-Structures/Nowak-Collins/p/book/9780429107467

Shayanfar, M., Ghanooni Bagha, M., & Jahani, E. (2015). *Reliability theory of structures*. Iran: Tehran, University of Science and Technology Publications. (In Persian).

Sorensen, J. D. (2004). *Structural reliability theory and risk analysis*. Denmark: Aalborg, Institute of Building Technology and Structural Engineering Aalborg University.

Zhang, S., Wang, G., Wang, C., Pang, B., & Du, C. (2014). Numerical simulation of failure modes of concrete gravity dams subjected to underwater explosion. *Engineering Failure Analysis*, 36, 49-64. https://doi: org/10.1016/j.engfailanal.2013.10.001.

APPENDIX 1

Nomenclature

Symbols	
d	plowing depth (cm)
E_s	Soil Young's modulus (kPa)
E_m	Moldboard Young’s modulus (kPa)
$\boldsymbol{e_i}$	Observed value
$\boldsymbol{F}(\mathbf{x})$	Cumulative distribution function
F_z	draft (longitudinal) force per bottom body (kN)
F_x	Lateral force per bottom body (kN)
F_y	Vertical force per bottom body (kN)
$\boldsymbol{F_R}(\boldsymbol{Q})$	The function of the cumulative distribution of the system resistance
$\boldsymbol{f_x}(\boldsymbol{x})$	Probability density function
$\boldsymbol{g}(\boldsymbol{R},\boldsymbol{Q}),\boldsymbol{g}(\mathbf{x})$	Limit state function
$\boldsymbol{N_F}$	Number of structural failure times
N	Number of repetitions
$\boldsymbol{n_i}$	Value of the function
P_f	Probability of failure
Q	Load
$\boldsymbol{Q_i}$	Load on the i element (part)
R	Resistance
$\boldsymbol{R_i}$	Resistance of the i element (part)
v	plowing speed (m s^{-1})
$\boldsymbol{\sigma_g}$	Standard deviation of the limit state function
$\boldsymbol{\sigma_Q}$	Standard deviation of the load function
$\boldsymbol{\sigma_R}$	Standard deviation of the resistance function
$\boldsymbol{\sigma_y}$	Yield stress (kPa)
σ_v	Von-Mises stress
σ	Standard deviation (in normal distribution)
σ'	Standard deviation (in lognormal distribution)
$\boldsymbol{\sigma_{max}}$	Maximum Von-Mises stress
σ_c	Compressive yield stress (kPa)
ρ	Density (g cm^{-3})
$\boldsymbol{\rho_{RQ}}$	Correlation coefficient between the two random variables of load and resistance
β	Reliability index
ξ	Internal angle of friction, Drucker-Prager (°)
$\boldsymbol{\mu}$	Mean (in normal distribution)
$\boldsymbol{\mu}'$	Mean (in lognormal distribution)
$\boldsymbol{\mu_g}$	Mean of the limit state function
$\boldsymbol{\mu_Q}$	Mean load function
$\boldsymbol{\mu_R}$	Mean resistance function

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مقاله علمی- پژوهشی

تحلیل قابلیت اعتماد سازه گاوآهن برگردان‌دار سوار به روش شبیه‌سازی مونت کارلو

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قابلیت اعتماد
گاوآهن برگردان‌دار

چکیده - استفاده از مفهوم قابلیت اعتماد به عنوان یک رویکرد طراحی جدید و سودآور می‌تواند طراحی و ساخت ماشین‌های خاک‌ورزی را بهینه کند. در این تحقیق به منظور انجام تحلیل قابلیت اعتماد بر روی شاسی یک گاوآهن برگردان‌دار، از روش شبیه‌سازی مونت کارلو (MCS) استفاده گردید. بدین منظور مدل کاملی از یک گاوآهن برگردان‌دار سه خیش سوار به عنوان تابع حالت حدی در نظر گرفته شد. پارامترهای تصادفی خاک اعمال گردید و نیروهای اثر متقابل گاوآهن با خاک به روش اجزاء محدود، شبیه‌سازی (finite element method, FEM) شد. خروجی مورد نظر، نیروهای عکس‌العمل خاک بر گاوآهن در بحرانی‌ترین سرعت و عمق شخم بود. سپس با اعمال نیروهای به‌دست آمده از مدل اجزاء محدود و همچنین در نظر گرفتن مدول یانگ شاسی به عنوان متغیر تصادفی، تحلیل استاتیکی شاسی در تکرارهای مختلف انجام و تمرکز تنش بر روی محل‌های مختلف شاسی مشخص گردید. سپس احتمال خرابی (P_f) و شاخص قابلیت اعتماد (β) محل‌های مختلف شاسی محاسبه گردید. نتایج شبیه سازی مونت‌کارلو نشان داد که بیشترین احتمال خرابی به ترتیب در میله عرضی، ساقه خیش، مهاربند و دکل با مقادیر ۱، ۰/۲۹۶، ۰/۱۶۵و ۰/۰۳۳ رخ داده که نشان‌دهنده عدم اطمینان طراحی در این قسمت‌ها می‌باشد، بنابراین تقویت یا بهینه‌سازی قسمت‌های ذکر شده شاسی گاوآهن برگردان‌دار ضروری به نظر می‌رسد.