Computers and Electronics in Agriculture 109 (2014) 162–171

Contents lists available at ScienceDirect

Computers and Electronics in Agriculture

journal homepage: www.elsevier.com/locate/compag

Reliability-based design optimization of shank chisel plough using optimum safety factor strategy

G. Kharmanda [a,*], M-H. Ibrahim [b], A. Abo Al-kheer [c], F. Guerin [b], A. El-Hami [d]

[a] Division of Solid Mechanics, Lund University, Lund, Sweden
[b] Ecole d'Ingénieurs de l'Université d'Angers, Angers, France
[c] Faculty of Agricultural Engineering, University of Aleppo, Aleppo, Syria
[d] INSA de Rouen, LOFIMS, St Etienne du Rouvray, France

ARTICLE INFO

Article history:
Received 4 June 2014
Received in revised form 27 July 2014
Accepted 10 September 2014

Keywords:
Design optimization
Structural reliability
Random variables
Soil properties
Soil tillage equipment
Optimum safety factors

ABSTRACT

Reliability integration into tillage machine design process is a new strategy to overcome the drawbacks of classical design approaches and to achieve designs with a required reliability level. Furthermore, design optimization of soil tillage equipments under uncertainty seeks to design structures which should be both economic and reliable. The originality of this research is to develop an efficient methodology that controls the reliability levels for complex statistical distribution cases of random tillage forces. This developed strategy is based on design sensitivity concepts in order to determine the influence of each random parameter. The application of this method consists in taking into account the uncertainties on the soil tillage forces. The tillage forces are calculated in accordance with analytical model of McKyes and Ali with some modifications to include the effect of both soil–metal adhesion and tool speed. The different developments and applications show the importance of the developed method to improve the performance of the soil tillage equipments considering both random geometry and loading parameters. The developed method so-called OSF (Optimum Safety Factor) can satisfy a required reliability level without additional computing time relative to the deterministic design optimization study. Since the agricultural equipment parameters are extremely nonlinear, we extended the OSF approach to several nonlinear probabilistic distributions such as lognormal, uniform, Weibull and Gumbel probabilistic distribution laws.

1. Introduction

In the deterministic design optimization (Arora, 1989; Haftaka and Gurdal, 1991), the designer aims to reduce the engineering design cost without caring about the effects of uncertainties concerning materials, geometry and loading. The resulting optimal solution may therefore represent an inappropriate reliability level. However, the integration of reliability analysis during the optimization process leads to reduce the structural weight in uncritical regions that does not only provide an improved design but also a higher level of confidence in the design. This model is called Reliability-Based Design Optimization (RBDO). Here, we distinguish three approach families: Coupled, Decoupled and Single Loop Approaches. The classical coupled approach can be carried out in two separate spaces: the physical space and the normalized space (two nested optimization problems). Since many repeated searches are needed in the above two spaces, the computational time for such an optimization is a big problem. The solution of the above nested problems leads to very high computational cost, especially for large-scale structures (Feng and Moses, 1986). The major difficulty lies in the structural reliability evaluation, which is carried out by a special optimization procedure. The decoupled approach such as SORA (Sequential Optimization and Reliability Assessment) is carried out in two successive loops (Du and Chen, 2004). In order to improve the numerical performance, a single loop approach such as OSF (Optimum Safety Factor) can be efficiently applied on linear cases (Kharmanda et al., 2009). The distributions of soil–tool forces are established to design soil tillage equipment such as shank chisel plough (Abo Al-kheer, 2010). In this paper, the OSF method is extended to several nonlinear probabilistic distributions. An efficient method is developed based on the optimality conditions. In this work, we use a statistical study of the soil tillage forces, based on soil property randomness.

* Corresponding author.
E-mail address: mgk@scs-net.org (G. Kharmanda).

http://dx.doi.org/10.1016/j.compag.2014.09.001
0168-1699/

2. Mechanical properties of soil

The working part of tillage equipment (ex: plow bottoms in moldboard plows, disk blades in disk plows) receiving energy from the tractor or other source works the soil and changes its state and properties. To determine the influence between the soil and tillage tool, we should determine the distribution type for each soil mechanical properties. The mechanical properties of soil which are important during soil-working, that is, properties which influence the nature of the process, hence the properties which have effects on the forces acting on the tillage tool are: Soil bulk density, Angle of internal friction, Angle of external friction, Cohesion and Adhesion. We elaborated a table of 32 samples of the above five mechanical properties of soils from our previous work (Abo Al-kheer, 2010). This data presented in Appendix, can be helpful to establish the soil tillage force probabilistic model.

3. Soil tillage forces

Many methods and models had been used to predict the forces acting on the tillage tool. However, the majority of researchers have used the general earth pressure model, proposed by Reece, 1965. The total force acting on the tillage tool can be written as follows:

$$P = P_\gamma + P_c + P_{ca} + P_q + P_a \tag{1a}$$

Here, P is the total soil cutting force acting on the tillage tool (kN), P_γ is the force acting on the tillage tool caused by soil gravity (kN), P_c is the force acting on the tillage tool caused by cohesion (kN), P_{ca} is the force acting on the tillage tool caused by adhesion (kN), P_q is the force acting on the tillage tool caused by surcharge pressure (kN) and P_a is the force acting on the tillage tool caused by tool speed (kN).

In our work McKyes and Ali's model (1977), as shown in Fig. 1, was used to estimate the forces acting on a tillage tool with three main modifications (Abo Al-kheer et al., 2011). The effects of soil–tool adhesion and tool speed were taken into account. The total force can be written according to the Equation (1a) as:

$$P = \left(\gamma d^2 N_\gamma + cdN_c + c_a dN_{ca} + qdN_q + \gamma v^2 dN_a\right)w \tag{1b}$$

where γ is the soil specific weight in (kN/m^{-3}), d is the tool working depth in (m), N_γ is the gravity coefficient (dimensionless), c is the soil cohesion in (kPa), N_c is the cohesion coefficient (dimensionless), c_a is the soil–tool adhesion in (kPa), N_{ca} is the adhesion coefficient (dimensionless), q is the surface surcharge pressure in (kPa), N_q is the surcharge pressure coefficient (dimensionless), v is the tool speed in (m/s), N_a is the inertial coefficient (dimensionless) and w is the tool width in (m). Dimensionless coefficients (N_γ, N_c, N_{ca}, N_q, N_a) can be determined with respect to the soil failure pattern proposed by McKyes and Ali (1977).

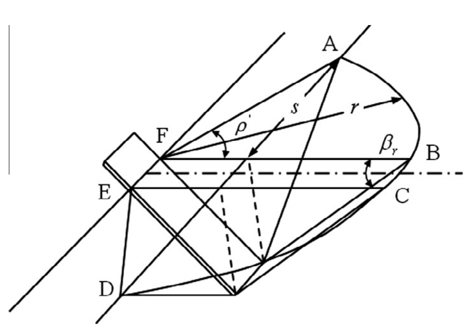

Fig. 1. Soil failure model for narrow blades, after McKyes and Ali (1977).

Furthermore, the width of the side crescent was calculated using an empirical regression equation and the rupture angle β_r was obtained by minimizing the total force.

The horizontal and vertical forces were calculated using the following two equations, respectively:

$$P_H = P\sin(\alpha + \delta) + c_a dw\cos(\alpha) \tag{2a}$$

$$P_V = P\cos(\alpha + \delta) - c_a dw \tag{2b}$$

where P_H is the horizontal force in (kN) and P_V is the vertical force in (kN). According to Eqs. (1) and (2), the tillage system parameters considered for the calculation of the horizontal and vertical forces can be grouped into three main categories: soil engineering properties, tool design parameters and operational conditions.

4. Structural reliability

In structural reliability theory many effective techniques have been developed during the last 40 years to estimate the reliability, namely FORM (First Order Reliability Methods), SORM (Second Order Reliability Method) and simulation techniques (Hasofer and Lind, 1974). Here, we consider two kinds of variables: Design variables and Random variables. The image of the random variables in the standard normalized space is denoted **u**, calculated by: **u** = T(**y**) where T(**y**) is the probabilistic transformation function (Fig. 2). For a given failure scenario, the reliability index β is evaluated by solving a constrained minimization problem:

$$\beta = \min\ d(\mathbf{u}) \quad \text{subject to}:\ H(\mathbf{u}) = 0 \tag{3}$$

with

$$d = \sqrt{\sum u_i^2}$$

where **u** is the vector modulus in the normalized space, measured from the origin see Fig. 2.

The solution to problem (3) defines the *Most Probable failure Point (MPP)*, see Fig. 2. The resulting minimum distance between the limit state function $H(\mathbf{u})$ and the origin, is called the reliability index β. The results are subjected to classical difficulties in nonlinear programming: existence of local minima, gradient approximation and computational time. The random variables are assembled in the vector **y** and represent the structural uncertainties which are identified by probabilistic distributions. These variables can be geometrical dimensions, material characteristics or applied external loading (Hasofer and Lind, 1974).

5. Reliability-Based Design Optimization (RBDO)

Traditionally, for the reliability-based optimization procedure we use two spaces: the physical space and the normalized space see Lemaire, 2005. Therefore, the reliability-based optimization is performed by nesting the following two problems:

Problem I: Optimization problem: this problem seeks to minimize an objective function subject to deterministic constraints and reliability requirements which is defined as follows:

$$\begin{array}{ll} \min & f(\mathbf{x}) \\ \text{subject to} & g_k(\mathbf{x}) \le 0, \quad k = 1, \ldots, K \\ \text{and} & \beta(\mathbf{x}, \mathbf{u}) \ge \beta_t \end{array} \tag{4}$$

where $f(\mathbf{x})$ is the objective function, $g_k(\mathbf{x}) \leqslant 0$ are the associated constraints, $\beta(\mathbf{x}, \mathbf{u})$ is the reliability index of the structure, and β_t is the target reliability index.

Problem II: Reliability analysis: the reliability index $\beta(\mathbf{x}, \mathbf{u})$ is the minimum distance between the limit state function $H(\mathbf{x}, \mathbf{u})$ and the