Improvement of Tractor Operator Safety by Multibody-FEM Techniques: The Influence of Soil Modelling

Mangialardi L.[1], Pascuzzi S.[2], Soria L.[1]
[1]*Politecnico di Bari, DIMeG – Mechanical Design Section*
V.le Japigia 182 – 70126 Bari, ITALY
Tel. +39 080 596 2710 – 2813, Fax +39 080 596 2810 – 2777
luigi.mangialardi@poliba.it, soria@poliba.it
[2]*University of Bari – PRO.GE.SA. – Mechanics Section*
Via Amendola 165/A – 70126 Bari, ITALY
Tel. +39 080 544 2214, Fax +39 080 544 2214
simone.pascuzzi@agr.uniba.it

Abstract

Most of the serious accidents in agriculture occur in the area of tractor roll-over. In order to reduce the number of work accidents, manufacturers have mandatory to equip their tractors with ROPS and seat safety belt anchorages, according to the European Community directive 2003/37/EC.

In this field of very high interest for worker safety, we have been carrying out a research activity aimed to analyse the injuries to operators and the effectiveness of restraint systems, by using a multibody-FEA approach. In particular the Madymo code is utilised (MAthematical DYnamic MOdels, TNO Automotive Safety Solutions).

In a previous paper we analysed the roll-over dynamics of a wheeled tractor with narrow track, placed on a slope, by means of a pure multibody scenario. Both the tractor structure and the ground were indeed modelled as infinitely rigid. In this paper the behaviour of two typical type of soil have been implemented in the model (by means of a FE description), analysed and compared with that of the rigid one. The aim of the study is to analyze how the soil mechanical strength affects the results of the accident dynamics simulation, by comparing the values both of the kinematic parameters and of the operator biological traumas. A better, more realistic description of all the interesting quantities is obtained, as expected.

Keywords: roll-over, restraint systems, dummies, injuries, soil

Introduction

Most of the serious accidents in agriculture occur in the area of tractor roll-over. As it is well known, ROPS and safety belts constitute the best option to avoid fatal consequences (ISPESL 2002, Comer *et al.*, 2003, Nichol *et al.*, 2005). These roll-over protective systems, indeed, allow to absorb the impact energy of an overturning vehicle without violating the DLV (Deflection Limiting Volume) and restrict driver movements inside the aforementioned clearance zone (Myers and Pana-Cryan, 2000, Nichol, 2005).

The European Community directives and the international Standards concerning the homologation of agricultural and forestry tractors for road circulation (EC 2003, EEC 1979, EEC 1986, EEC 1987, ISO 1989, OECD 2005) have by now obliged manufacturers to provide their tractors with a ROPS and a seat belt anchorage. Agricultural tractors are then equipped with a strong frame or a cab and with a pelvic restraint system, fastened to two points belonging to the driver seat or, less frequently, to the tractor chassis (Molari and Rondelli, 2007).

In this area of high interest for worker safety, we have carried out a research activity aimed to study the injuries caused by the overturning of the tractor and the effectiveness of the operator restraint systems, by means of a multibody-FEA code, Madymo (MAthematical DYnamic MOdels, TNO Automotive Safety Solutions) (Mangialardi and Soria, 2005, Mangialardi *et al.*, 2008).

The Madymo solver is generally utilised for the analysis of road vehicle safety related problems, to study the dynamic behaviour of safety structures and devices involved in simulated crashes, even evaluating the occupants biological injuries (Ambrosio, 2001, EuroNCAP, 2004, Kleinberger *et al.*, 1998). This is possible because the code includes libraries of numerical dummies, as models of seat belts and airbags (TNO Automotive Safety Solutions, 2009) which allow to reproduce the dynamic behaviour of the real instrumented dummies usually employed in real vehicle crash tests.

In a previous paper, we analysed the overturning dynamics of a wheeled tractor with narrow track, with the purpose of comparing the operator biological traumas in the cases (i) he was restrained with a pelvic belt or (ii) not restrained at all. As a starting point, in that study the structure of the tractor and the soil were both considered infinitely rigid, leading to a pure multibody scenario (Mangialardi *et al.*, 2008).

In this paper, we have improved the simulation model, by considering real stiffness values and constitutive material model of two different type of soil: The clay- and the sand-based ones. We have compared the results coming from the tractor-soil impact simulated dynamics obtained in those two cases with that obtained in the case of rigid soil. In the study, differently from the previous one, only the case of operator restrained with a 2-point pelvic belt is considered.

A more realistic description of all the interesting kinematic quantities has been obtained, as expected. High picks on time-varying accelerations related to step variations of the linear and the angular momentum, typical of hits between rigid bodies, are no longer present.

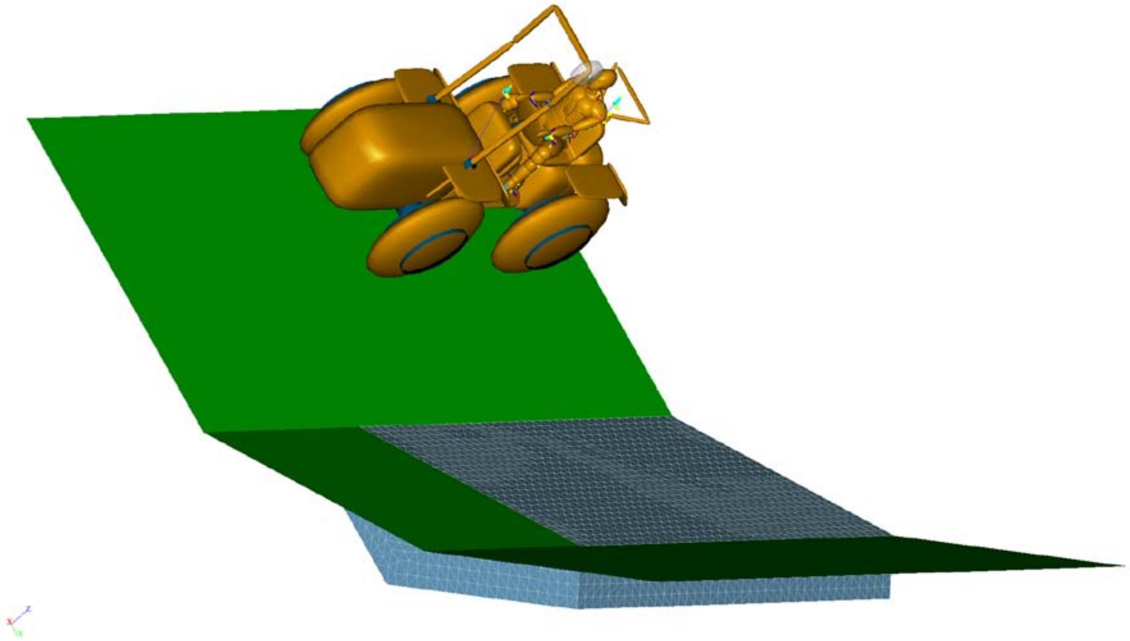


Figure 1. 3D view of the accident scenario (the initial position of the simulations is represented)

Materials and methods

The tractor

A narrow track wheeled tractor equipped with two ROPS (safety frames), selected among the ones available on the market, has been considered. The 3D multibody model, obtained moving from 2D drawings, has been reproduced with native hyper-ellipsoidal Madymo surfaces and consists of seven parts: (i) the body frame, (ii) the four wheels, (iii) the front and the rear safety ROPS. This model and the inertial frame used for the simulation are represented in Figure 1.

To each of the surfaces a body reference frame is rigidly connected and the whole spatial distribution of the mass (centre of gravity and inertia tensor) is declared with respect to this frame. The entire tractor model is then obtained by constraining the parts each other, by means of kinematic joints. The safety frames are supposed to be fixed to the body frame, by means of two brackets. Each of the four wheels is connected to the body frame by a cylindrical joint. The whole tractor model is then declared in the input scenario by means of a free joint.

When the tractor does not have any contact taking place with the ground, e.g. in a particular phase of the accident, the model has, in conclusion, 10 degrees of freedom (d.o.f.), the 6 rigid body motion d.o.f. and the 4 wheel rotations.

The soil

The tractor interacts with the soil by unilateral contacts. During the accident dynamics, every part of the tractor could actually come into contact with the soil, giving rise to the resultant number of d.o.f. of the whole scenario, in each instant of time.

A typical roll-over accident is analysed. The soil is supposed to be composed of three planes of different slope (Figure 1). At the beginning of the simulated dynamics, the tractor is positioned on the plane having the highest slope, in a way that the resultant weight force is able to make the tractor rolling over. A four node tetrahedral finite element model of the intermediate soil plane has been implemented in the accident scenario to take into account its solid behaviour. An isotropic elastic, perfectly plastic constitutive model has been utilised. The intermediate plane is actually the one which the rolling over tractor ends to hit on.

To model the dynamic behaviour of an agrarian soil subjected to time-varying mechanical forces proves to be rather difficult due to the strong variability of the parameters (texture, porosity, humidity, plasticity, etc.) and as a consequence of the physical-mechanics properties of the soil itself (Biondi, 1999, Peruzzi, 1997).

Generally, in the technical literature, a certain soil is described as a transversally isotropic medium and the theory of the plasticity is utilised (Lancellotta, 1987).

In this study we have considered two types of soil having quite different mechanical properties: (i) a sand-based soil and (ii) a clay-based soil. The parameter values utilised in the accident model, are reported in Table 1.

Table 1. Mechanical property parameters of the two considered soils

soil	mass density [kg/m^3]	Young's modulus [MPa]	Poisson's ratio	yield stress [kPa]
sand	1600	200	0.3	200
clay	1800	40	0.3	120

The dummy

The tractor operator is simulated by means of a numerical dummy chosen among the ones available in the Madymo libraries, the Hybrid III 50th percentile male dummy, which is the most frequently utilised in the crash tests and in all the NCAP programs (New Car Assessment Programs). The dummy numerical models available in the Madymo libraries are multibody systems, composed by simple geometry bodies and/or FEM models assembled with kinematics joints and restraints, which reproduce the connections present in the instrumented real dummies usually employed in the crash tests.

The evaluation of biological damages by multibody techniques: The injury parameters

An estimation of the biological traumas that occur to occupants of a vehicle involved in a crash can be obtained through the evaluation of the values of the so-called injury parameters. The injury severity can be evaluated by utilising the corresponding injury criteria, i.e. by comparing the calculated value of each parameter with a certain threshold value. This thresholds have been established with the progresses made in the field of biomechanics, by carrying out experimental test campaigns on volunteers and dead bodies (Ambrosio, 2001, EuroNCAP, 2004, Kleinberger *et al.*, 1998).

The following injury parameters and the corresponding criteria have been utilised in this paper:

- The Head Injury Criterion (HIC) for the estimation of head injuries. It is evaluated by means of a suitable integral average of the head centre of mass acceleration in a time window of not more than 36 ms. The criterion threshold value is 1000 $(m/s^2)^{2.5}s$ during an impulsive frontal shock. It has to be stressed that head sudden rotations are not considered in HIC evaluation.
- The Neck Injury Predictor (N_{ij}) for the estimation of neck injuries. It is evaluated by the calculation of the forces and moments acting on the occipital region. The values achieved by these quantities are put in a suitable dimensionless form by using critical values, that depend on the dummy typology and on the neck loading conditions. They do exist four types of N_{ij}, indeed, one in each of the possible cases, tension – extension (N_{TE}), tension – flexion (N_{TF}), compression – extension (N_{CE}), compression – flexion (N_{CF}). In all the cases, to not have severe damages to the neck, it has to be $N_{ij} < 1$.
- The 3 ms Criterion (3ms) for the estimation of damages occurring to thorax. Thorax injuries are the most critical after head injuries. To not have severe damages, the thorax centre of mass has not to undergo an acceleration higher than 60 g for a time longer than 3 ms.

Results

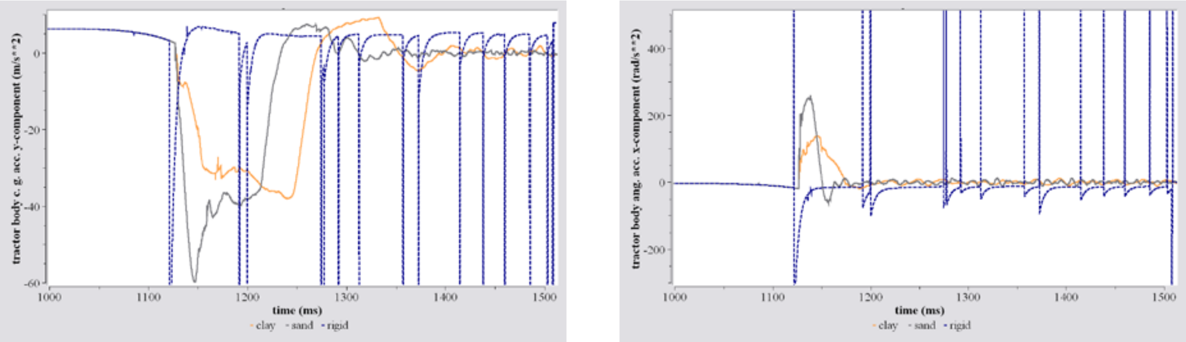
The roll-over kinematics

In Figures 2 and 3 the kinematic quantities of main interest, i.e. the longitudinal (*x*-) component of the tractor body angular velocity and acceleration and the transversal (*y*-) component of the tractor body centre of gravity velocity and acceleration are represented as functions of time in the three cases of soil considered, (i) clay, (ii) sand and (iii) rigid.

In the case of rigid soil, as expected, the tractor bounces on it with a series of following shocks, in each one of which one has a step variation of the angular velocity vector (Figure 3 b) and an extremely high peak value of the angular acceleration (Figure 2 b). This behaviour is actually far from that it is the real one. Similar consideration can be made referring to velocity and acceleration of the tractor body centre of gravity (Figure 3 a and 2 a), which in average moves down along the slope.

Both in the cases of sandy and clayey soil, instead, all the acceleration peaks reduce to realistic values and, in particular, the time interval in which one has the main first rebound of the tractor body becomes wider.

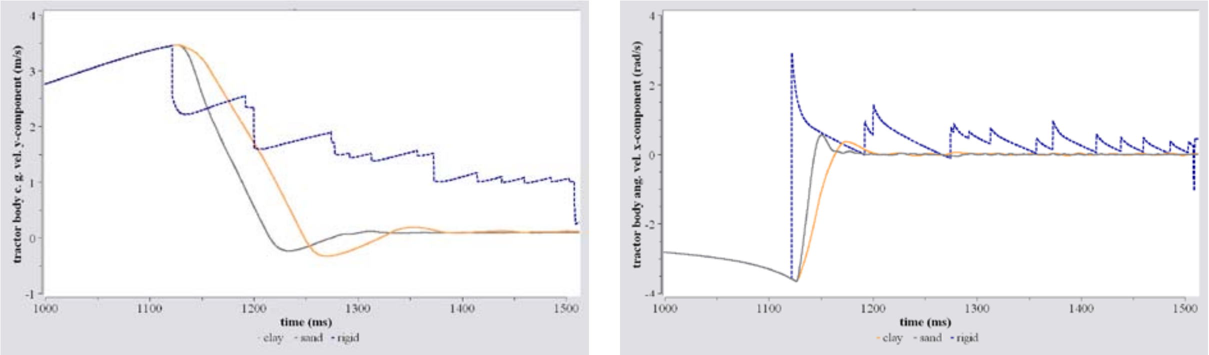
In conclusion a slower variation of the kinematic quantities is obtained with a consequent more realistic representation of the roll-over dynamics of the tractor.



(a) (b)

Figure 2. The *y*-component of the tractor body centre of gravity acceleration (a) and the *x*-component of the tractor body angular acceleration (b) as functions of time

In Figure 4 the final time of the simulations is represented. The soil plastic deformations related to the interaction with the tractor body and mainly with the front safety frame can be clearly seen. The algorithm utilised to detect a multibody-FEM contact is basically related to the evaluation of the virtual relative penetration between the two interacting parts. This quantity allows the evaluation of the reactive forces due to the contact between the nodes of the soil FEM mesh and the hyper-ellipsoidal surfaces of the multibody tractor.



(a) (b)

Figure 3. The *y*-component of the tractor body centre of gravity velocity (a) and the *x*-component of the tractor body angular velocity (b) as functions of time

The biological traumas caused to the operator

In Table 2 the values of the said injury parameters are reported in the case of operator restrained with a 2-point pelvic belt, for the two different examined type of soil.

First of all one has to notice that none of the injury parameters overcomes the corresponding threshold value and this highlights the utility of the seat safety belt, as expected.

Moreover the comparison of the injury parameter values obtained in the different simulated cases of soil points out that the operator traumas seem to increase a bit as the stiffness of the soil decreases: the injuries evaluated in the case of clayey soil are higher than the ones obtained with a sandy soil and these last ones are higher than those related to a rigid soil.

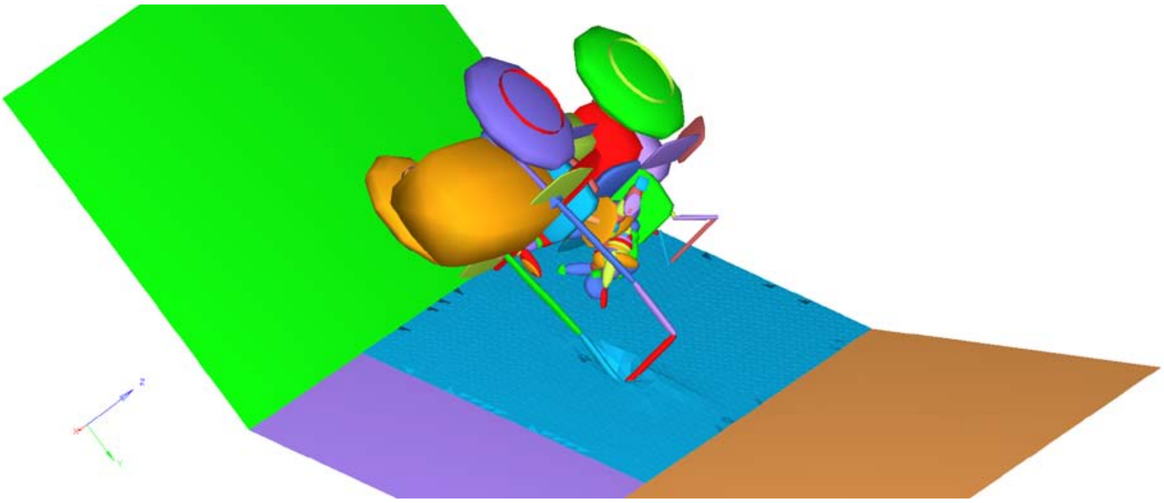


Figure 4. End of the simulation: it is possible to visualise the contacts between the dummy-tractor system and the deformable soil

This result is not surprising since the different soil mechanical strength affects the whole tractor dynamics and, in particular, the amount of penetration of the ROPS into the soil, so that also the safety volume (DLV) becomes a function of the soil deformation: it becomes smaller as the stiffness of the soil decreases. As a conclusion, the interaction between the tractor operator and the soil gets more likely as the deformation of the soil increases.

Table 2. Comparison of the main injury parameters in the case of operator restrained with a 2-point pelvic belt considering each one of the examined soils

injury parameter	**injury criterion**	**clayey soil**	**sandy soil**	**rigid soil**
HIC $[(m/s^2)^{2.5}s]$	< 1000	329.10	244.84	13.015
N_{TE}	< 1	0.27029	0.29038	0.22677
N_{TF}		0.15709	0.10052	0.054920
N_{CE}		0.45020	0.39971	0.039257
N_{CF}		0.57922	0.29627	0.0096685
3 ms $[m/s^2]$	< 60 g	138.62	105.65	133.82

Conclusions

The scenario of a typical roll-over of a tractor has been reproduced in the multibody-FEA Madymo environment (TNO Automotive Safety Solutions) and, in particular, in the simulated scenario the structure of the tractor has been considered infinitely rigid, whilst two different types of soil, a clay-based soil and a sand-based one, have been modelled as deformable by means of a FE description. The dynamic behaviour of those two kind of soils have been then compared with the one coming from a similar scenario in which, instead, an infinitely rigid ground is considered.

The obtained results show clearly how useful is the seat belt in confining the operator in the clearance zone so that all the injuries are reduced. Moreover from a kinematic point of view the deformation of the soil produce close to real acceleration and velocity values with respect to those obtained considering a rigid soil.

From a dynamic point of view, the higher are the soil plastic deformations the bigger is the penetration of the ROPS in the soil so to reduce the safety volume and to make more possible the interactions between the operator and the soil. As a consequence the injury severity seems to get a bit higher, with reducing values of the soil stiffness.

In a further, final improvement of the simulation model, the deformability of the safety ROPS will be also taken into account, that again is expected to lead to a further reduction of the safety limiting area of the operator and hence to a complete, close to real estimation of the trauma severity.

Acknowledgements

Each of the authors contributed in equal parts to this work.

References

Ambrósio, J. A. C. 2001. Crashworthiness. Energy Management and Occupant Protection, vol. 423, CISM, SpringerWien NewYork.

Biondi P. 1999. Meccanica agraria. UTET Torino.

Comer R. S., Ayers P., Wang X., Conger J. B., Troutt P. 2003. Evaluation of ASAE standard S547 for the continuous roll testing on front driven mowers. ASAE Paper No. 38005.

EC 2003. Directive 2003/37/EC of the European Parliament and of the Council of 26 May 2003 on type-approval of agricultural or forestry tractors, their trailers and interchangeable towed machinery, together with their systems, components and separate technical units and repealing Directive 74/150/EEC. European Community.

EEC 1979. Council Directive 79/622/EEC of 25 June 1979 on the approximation of the laws of the Member States relating to the roll-over protection structures of wheeled agricultural or forestry tractors (static testing). European Community.

EEC 1986. Council Directive 86/298/EEC of 26 May 1986 on rear- mounted roll-over protection structures of narrow-track wheeled agricultural and forestry tractors. European Community.

EEC 1987. Council Directive 87/402/EEC of 25 June 1987 on roll-over protection structures mounted in front of the driver's seat on narrow-track wheeled agricultural and forestry tractors European Community.

European New Car Assessment Programme (EuroNCAP) 2004. Assessment protocol and biomechanical limit (version 4.1). Tech. rep.

ISO 1989. ISO 3776, Tractor for agriculture—seat belt anchorage. International Organisation for Standardisation, Geneva.

ISPESL 2002. Requisiti di sicurezza dei trattori agricoli e forestali. [Safety requirements of agricultural and forestry tractors.]. Il sole 24 ore, 16, 1-16.

Lancellotta R. 1991. Geotecnica. Zanichelli Editore Bologna

Kleinberger M., Eppinger R., Sun E., Kuppa S., Saul R. 1998. Development of improved injury criteria for the assessment of advanced automotive restraint systems. NHTSA. Tech. rep.

Mangialardi L., Soria L. 2005. Impiego di tecniche multibody per il miglioramento della sicurezza degli operatori di carrelli a forche. Atti del XVII Congresso AIMETA di Meccanica Teorica e Applicata, Firenze, 11-15 settembre 2005.

Mangialardi L., Pascuzzi S., Soria L. 2008. Use of simulation techniques to improve tractor operator safety. Proceedings of the International Conference «Innovation Technology to Empower Safety, Health and Welfare», Ragusa – Italy, September 15-17, 2008.

Molari G., Rondelli V. 2007. Evaluation criteria for the anchorage resistance of safety belts on agricultural tractors. Biosystems engineering, 97. 163-169.

Myers M. L. 2002. Tractor risk abatement and control as a coherent strategy. Journal of Agricultural Safety and Health, 8(2), 185-198.

Nichol C. I., Sommer H. J., Murphy D. J. 2005. Simplified overturn stability monitoring of agricultural tractors. Journal of Agricultural Safety and Health, 11(1), 99-108.

OECD 2005. Standard Codes for the Official Testing of Agricultural and Forestry Tractors. Organisation for Economic Cooperation and Development, Paris.

Peruzzi A., Sartori L. 1997. Lavorazione del terreno. EDAGRICOLE - Edizioni Agricole. Bologna

TNO Automotive Safety Solutions - Delft (NL) 2009. MADYMO Manuals - Release 7.1.