MATERIAL MODEL PARAMETERS IDENTIFICATION OF BLAST ENVIRONMENT

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Abstract: *In terms of designing or building new protective and security structures or equipment as a physical component of force protection, experimental verification of analytical or numerical calculations and vice versa becomes necessary. While the experiment can be performed on individual components, complex assessment of more complex variants or performing a parametric study is becoming more and more relevant in modelling and simulation domain. For this reason, there is a clear necessity to find the right connection between numerical simulation and experiment.*

Fast, nonlinear processes require nonlinear material models to capture the rate of deformation and material behaviour under extreme loads such as the effect of explosions or the impact of a projectile, i.e. the effects, which the theories and practices of protection of the population and troops are trying to minimize. The important part of the accuracy of computational models is the correct identification of the parameters of material models used in the simulations.

This paper deals with the simulation of explosion and its effects and identification and optimization of material parameters of the environment in which the explosion and the shockwave propagates, with a focus on the soil material model. The inverse identification method is based on a combination of the experimental measurement data and the computational methods implemented in the finite element solvers and optimization programs. The simulation proceed from experimental measurement curves of blast effects. For measured parameter in the air overpressure at specific measuring points was chosen, while ground-propagating shock wave was evaluated by measuring acceleration values. The numerical simulation took place in the LS-Dyna software environment interconnected with the Optislang optimization program.

Keywords: LS-DYNA, INVERSE IDENTIFICATION, FEM, NUMERICAL SIMULATION, SHOCK WAVE PROPAGATION, SOIL MATERIAL MODEL

1 Introduction

1.1 Motivation

In present day, protection against the destructive effects of the explosion is in the spotlight. List of these effects is broad and, for this reason, the principles and methods of protection extend to different fields of technical sciences. Among the most important are the direct effects of the increased pressure present near the epicentre of the explosion [1], followed by the accelerated fragments and, last but not least, the shock wave propagated in the air in the event of the above-ground explosion but also through the material, into which the waves step in or in which the explosion itself occurred. For force protection and the ability to assess the protective properties and level of resistance of buildings and other protective structures, it is essential to know and evaluate the magnitude of the destructive factors. In case of the possibility of damage to both, protective structures and critical infrastructure due to intentional or accidental explosion, it is advisable to investigate the shock waves themselves as well as the pressure and acceleration values that this wave is causing [2].

Unlike the propagation of the shock wave in air, the propagation of waves through the soil is more difficult to assess due to great variety of soil and rock types, as well as is the assessment of its effects due to variety of types of construction and buildings and its foundations. This thesis aims to show the methods for a correct and effective way to correctly identify and evaluate the parameters of the soil affecting the propagation of the shock wave in the soil and contribute to improve numerical simulation possibilities. The simulation and parameter identification present in this paper is based on the field test result of [3] and aims to further extend the possibilities of prediction, evaluation and assessment of dynamic loading effects on infrastructure [4].

1.2 Blast Pressure and Acceleration in Soils

Soils are generally a three-phase air-water-rigid matrix system. The mechanical properties of this environment depend on the macrostructure, which is difficult to accurately describe as it can be described, for example, in isotropic homogenous materials like steel. The plastic part of the material response plays an essential role. This is the main difference in soil and rock behaviour.

Another important loading response classification differentiate whether it is cohesive or incoherent soil.
Rock rocks can be considered to be a homogeneous, linearly elastic substance [5]. For soil, the mechanism of the deformation consist of two steps, which are being realized gradually. In the first phase, the solid component is deformed until the bond is broken. In the subsequent step, individual grains are shifted, compressed, and all soil components starting to work as one. This way the dry soils are damaged. In the case of soils with substantial contain of water under the shock loading, the loading is mainly transmits by the liquid component. The solid phase is applied only in units of hundreds to thousands of MPa or at a slower rate of loading when the water is pushed out of the pores [5].

In the case of shock loading caused by explosion, in the vicinity of the epicentre, the plastic deformations of the soils are far beyond the applicability of the Hook Law. Subsequently, a stable shock wave is formed that quickly loses energy and passes into elastic-plastic waves, which can be mathematically described. The effect and evaluation of such earth-waves on structures is the subject of discussion and various approaches, where most standards use a velocity amplitude value, after which the real possibility of a certain damage to the building and the categorization of the foundation soil is exceeded.

As the representative of the analytical prediction, opposite to widespread numerical simulations, the most used source of analytical assessment equations of the ground shock parameters The US Army Corps of Engineers Manual [1] can be mentioned. Working with the cube root scaled distance, two equations of the ground shock destructive effects, peak values of pressure and acceleration can be obtained as:

$$P_p = 0.407 f \rho_c \left(\frac{R}{W^{1/3}}\right)^{-n} \tag{1}$$

$$a_p = \frac{39.8fc}{W^{1/3}}\left(\frac{R}{W^{1/3}}\right)^{-(n+1)} \qquad (2)$$

where P_p is the peak pressure (Pa), f is a coupling factor, which is dependent on the scaled depth of the explosion - $d/W^{1/3}$, where d is the depth of the centroid of the explosive charge, ρ_c is the acoustic impedance, c is the seismic velocity, R is the distance from the source, W is the charge weight; n is an attenuation coefficient, and a_p is the peak acceleration. Manual provides classification of 5 type of soils with corresponding material parameters for the equations (Table 1) [1].

Table 1: *Mechanical properties of selected powder materials [1].*

Soil type	Density, $\rho(kg/m3)$	Seismic velocity, $c\ (m/s)$	Acoustic impedance, ρ_c $(Pa \cdot s/m)$	Attenuation coefficient n
(1) Heavy saturated clays and clay shale	1920-2080	>1524	3,9-40,68	1,5
2) Saturated sandy clays and sands with air voids < 1 %	760-1984	1524	29,38	2,25-2,5
3) Dense sand with high relative density , wet sandy clay with air voids > 4 %	1744 1920-000	487,68 548,64	9,944 10,848	2,5 2,5
(4) Sandy loam, loess, dry sands and backfills	1984	304,8	4,972	2,75
(5) Loose, dry sands and gravels with low relative density	1440-1600	182,88	4,972	2,75

2 Experimental data

In order to perform the numerical simulation and a material model identification of the soil, experimental data has to be obtain and analysed. For this purposed, and experimental data acquired from the field blast tests performed by [3] were used. By the usage of buried accelerometers situated in one line in defined distanced positions from the explosive charge, a time-acceleration curves were obtained together with the velocity of the shock wave computed from the data. Simulation and identification is focused on the two peak values of acceleration. The setup of the experiment is described through the computational model, which accurately depicts the experiment (Fig. 1).

Table. 2 shows the setup of experiment and its results, where the explosive charge of equivalent of 15 kg TNT was situated 1.6 m under the surface together with minimal and maximal values of acceleration measured with two accelerometers situated in the distance of 13 and 23 meters from the explosive charge.

Table 2: *Setup description and results of the experiment [3]*

#	Weight of charge	Distance [m]		Acceleration min/max $[m/s^2]$	
		1	2	1	2
12	15	13	23	4.4/-5,43	0.89/-1,36

3 Computational model

The aim of this phase was to create a computational model and to perform a numerical simulation of the explosion shock wave propagation in the soil environment. The simulation in substantial parts copies the experimental layout, i.e. a setup where the aim is to measure the peak acceleration given to the shock wave loaded sensors.

The computation model was prepared as a 2D problem with one axis of symmetry [6], resulting into significant savings of the computing time. For discretization of the soil occupied space, the Multimaterial 2D ALE elements were used with elements of the edge length of 2 mm, where, after the initial calculation, the mapping values from 2D to 2D was performed on elements with a diameter of 5 mm. Subsequently, a material model from the LS-DYNA library with the number 147 MAT_FHWA_SOIL [7] was assign to this part of the mesh.

The elastic properties of this soil are isotropic. The model is extended to include excess pore-water effects, strain softening, kinematic hardening, strain-rate effects, and element deletion [7].

The modified yield surface is a hyperbola fitted to the Mohr-Coulomb surface. At the crossing of the pressure axis (zero shear strength), the modified surface is a smooth surface and it is perpendicular to the pressure axis. The yield surface is given as:

$$F = -Psin\phi + \sqrt{J_2K(\theta)^2 + ahyp^2\,sin^2\phi} - c\,cos\phi = 0 \qquad (3)$$

where P is pressure, ϕ is internal friction angle, $K(\theta)$ is function of the angle in the deviatoric plane, $\sqrt{J_2}$ is a square root of the second invariant of the stress deviator, c is amount of cohesion, J_2 is the third invariant of the stress deviator, ahyp is parameter for determining how close to the standart Mohr-Cpulumb yield surface the modified surface is fitted.

To generalize the shape in the deviatoric plane, the standard Mohr-Coulomb $K(\theta)$ function was changed to a function:

$$K(\theta) = \frac{4(1-e^2)cos^2\theta + (2e-1)^2}{2(1-e^2)cos\theta + (2e-1)[4(1-e^2)cos^2\theta + 5e^2 - 4e]^{\frac{1}{2}}} \qquad (4)$$

where $cos3\,\theta = \frac{3\sqrt{3}J_3}{2J_2^{\frac{3}{2}}}$, $J_3$is the third invariant of the stress deviator, e is the material parameter describing the ratio of triaxial extension strength to triaxial compression strenght. The whole description of the model can be found in [7].

Creators of this model provide a comprehensive manual of the model together with filled Ls-Dyna material card in the manual, which is a great advantage and reason for usage of this model in numerical simulations, because in complex models many parameter values are unknown or are difficult to obtain from experiments, tests or other sources (Table 3). This set represented a starting point in the simulation and reverse identification process.

Table 3: *Soil material parameters according the manual, values for shear tests [7] (mm, kg, ms, GPa, kN),*

*MAT_FHWA_SOIL							
MID	*RO*	*NPLOT*	*SPGRAV*	*RHOWAT*	*VN*	*GAMMAR*	*INTRMX*
222	*2.350E-06*	*3*	*2.79*	*1.00E-06*	*1.1*	*0.0*	*10*
K	*G*	*PHIMAX*	*AHYP*	*COH*	*ECCEN*	*AN*	*ET*
0.003250	*0.001300*	*1.1*	*1.00E-07*	*6.200E-06*	*0.7*	*0.0*	*0.0*
MCONT	*PWD1*	*PWKSK*	*PWD2*	*PHIRES*	*DINT*	*VDFM*	*DAMLEV*
0.034	*0.00*	*0.00E-05*	*0.00*	*0.001*	*1E-05*	*6.0E-08*	*0.99*
EPSMAX							
0.80							

To simulate the explosion itself, an explicit approach to air and explosive modelling was used using multimaterial ALE formulation [6] of elements with assignment of the proper equation of state (EOS) to the used materials. In the initialization phase, the entire

ALE network was filled with air (EOS_Linear_Polynomial, Mat_Null, Table 4. and Table 5.).

Table 4: *Air material model parameters (mm, kg, ms, GPa, kN),*

*MAT_NULL							
MID	RO	PC	MU	TEROD	CEROD	YM	PR
555	1.235E-09	-1.235E-09	-1.0E-00	1.844E-11			

Table 5: *Equation of state parameters for the air (mm, kg, ms, GPa, kN),*

*EOS_LINEAR_POLYNOMIAL							
EOSID	C0	C1	C2	C3	C4	C5	C6
2	0.0	0.0	0.0	0.0	0.4	0.4	0.
E0	V0						
2.533E-04	1						

After the beginning of the simulation, the volumetric part of the soil elements were filled with explosive charge (*EOS_Wilkinson_Lee*, *Mat_High_Explosive_Burn*). (Table 6. and Table 7.)

Table 6: *Explosive material parameters (mm, kg, ms, GPa, kN),*

*MAT_HIGH_EXPLOSIVE_BURN							
MID	R0	D	PCJ	BETA	K	G	SIGY
444	1.650e-06	6930.0	21.0	0.0	0.0	0.0	0.0

Table 7: *Equation of state parameters for the explosive charge (mm, kg, ms, GPa, kN),*

*EOS_JWL							
EOSID	A	B	R1	R2	OMEG	E0	V0
3	371.2	3.23	4.15	0.95	0.30	7.0	1.0

A 15kg TNT equivalent defined cylindrical charge was placed 1.6 m under the surface (Fig.1) [8]. For a more detailed record of the acceleration values at nodes distanced 13 m and 23 m from the charge, a database command was added for recording the peak values of acceleration. Both nodes were situated 1.6 m underground.

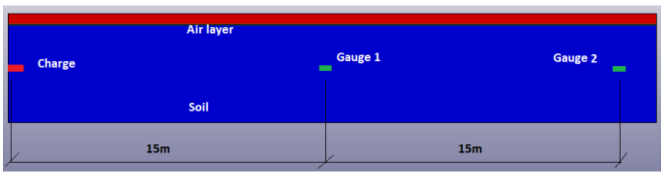

Fig 1. Computational model - setup

For the first step of the simulation, the simulation was launched on the fine meshed soil part to enhance the accuracy of the simulation. After that phase, the result were mapped [9] on more coarse mesh representing the whole setup due to significant computational time savings (Fig 2).

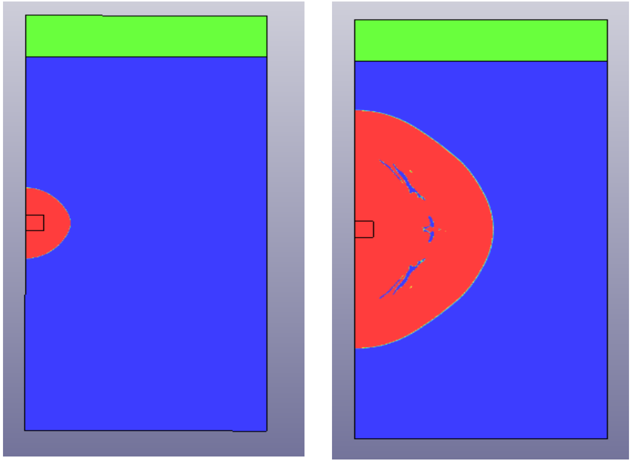

Fig 2. Propagation of wave – Initial step before mapping

On the Fig. 3 it can be seen the propagating wave has reached the final gauge point. At this time, the simulation was stopped and it was able to advance to the next step.

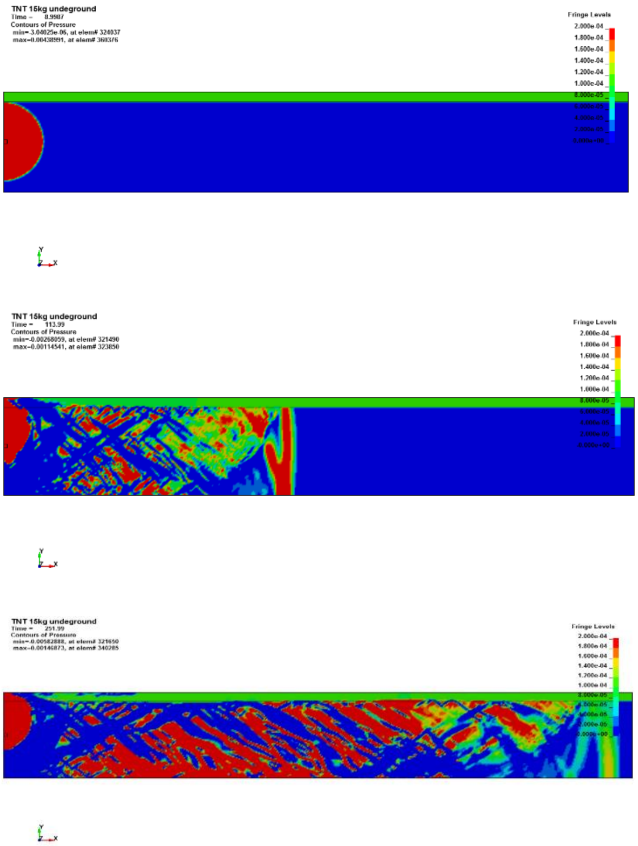

Fig 3. Propagating shock wave – pressure contours

Table 8 show the extracted peak values of acceleration in the gauge nodes.

Table 8: *Setup description and results of the experiment and simulation*

#	Weight of charge [kg]	Distance of gauges [m]		Acceleration min/max $[m/s^2]$	
		1	2	1	2
12	15	13	23	4.4/-5,43	0.89/-1,36
Simulation	15	13	23	4,8/-5,8	1,5/-1,4

4 Parameter identification

Inverse parameter identification is a set of methods and procedures used to find parameters in the material computational model used in the software environment of programs working on the finite element principle. Since only the exact values of the input parameters lead to the desired match of the simulation results with the experiment, finding them is a key part of the computational model creation. Inversion Parameter Identification of Maternal Model 147 MAT_FHWA_SOIL was used for text based interconnection of LS-Dyna and optimization software Optislang [9].

To simplify and reduced the computational time, four parameters of interest were chosen. Besides K - bulk modulus and G - shear modulus, $Dint$ –Volumetric strain at initial damage threshold and $Vdfm$ – Void formation energy, parameters connected with high strain effect and values of pressure, effects presented in the blast loading, were chosen for parameter identification with corresponding ranges of variability. $Damlev$ – Level of damage that will cause element deletion and $Epsmac$ – Maximum principal failure strain were set to values of 1 due to necessity of conservation of energy and ability to secure the propagation of the wave [7].

The objective function was set simply as the sum of squares of differences between the numerically-simulated maximal values of nodal acceleration obtained from text output database and corresponding experimentally measured maximal acceleration values from the field test. To minimize those function, and evolutionary algorithm was chosen [10].

A comparison of the values of acceleration and together with the newly found material parameter card in LS-Dyna can be seen in Table 9. and Table 10. It can be seen, that in order to increase the values of nodal accelerations in gauge points, it was necessary to increase the values of input parameters. Some of them in the order magnitudes compared to the initial values.

Table 9: *Setup description and results of the experiment and simulation, and parameter identification*

#	Weight of charge [kg]	Distance of gauges [m]		Acceleration min/max $[m/s^2]$	
		1	2	1	2
12	15	13	23	4.4/-5,43	0.89/-1,36
Simulation	15	13	23	3.51/-3.6	0,42/-0,83
Simulation - optimised	15	13	23	4,8/-5,8	1,3/-1,4

Table 20: *Soil material parameters after the inverse parameter identifications (mm, kg, ms, GPa, kN)*

*MAT_FHWA_SOIL							
MID	*RO*	*NPLOT*	*SPGRAV*	*RHOWAT*	*VN*	*GAMMAR*	*INTRMX*
222	*2.35-06*	*3*	*2.79*	*1.00E-06*	*1.1*	*0.0*	*10*
K	*G*	*PHIMAX*	*AHYP*	*COH*	*ECCEN*	*AN*	*ET*
0.01750	*0.00822*	*1.1*	*1.0E-07*	*6.200E-06*	*0.7*	*0.0*	*0.0*
MCONT	*PWD1*	*PWKSK*	*PWD2*	*PHIRES*	*DINT*	*VDFM*	*DAMLEV*
0.034	*0.00*	*0.00*	*0.00*	*0.001*	*1.9E-03*	*5.0E-02*	*1.0*
EPSMAX							
1.00							

5 Conclusion

Inverse parameter identification of material model parameters of soil were performed in this paper. The problem of wave propagation in the soils is very complex and with combination of extreme loading caused by explosion pose a challenge for material modelling. The more complex the model is, the more stand o necessity to exclude the some parameters from the identification process to secure reasonable computing time. Another restricting condition for the accuracy of the results of the simulation is the computational model and its complexity together with refinement of the finite element mesh. More complex field tests and parameter identification is necessary for other cases of blast loading [11]. Identified values of the parameters of the soil model represent a way how to simulate effects of blasts in the soil and can be used to assess the damage of the facilities and infrastructure buried or in contact with the soil ground [12, 13]. To assess the effects of blast loading on the laid critical infrastructure is the goal of the next simulation and experimental study of the authors.

6 References

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