Soil Dynamics and Earthquake Engineering 28 (2008) 20–35

SOIL DYNAMICS AND EARTHQUAKE ENGINEERING

www.elsevier.com/locate/soildyn

Parameterization of the porous-material model for sand with different levels of water saturation

M. Grujicic[a,*], B. Pandurangan[a], R. Qiao[a], B.A. Cheeseman[b], W.N. Roy[b], R.R. Skaggs[b], R. Gupta[b]

[a]*Department of Mechanical Engineering, Clemson University, Clemson, SC 29634, USA*
[b]*Army Research Laboratory—Survivability Materials Branch, Aberdeen, Proving Ground, MD 21005-5069, USA*

Received 2 January 2007; received in revised form 26 April 2007; accepted 7 May 2007

Abstract

The experimental results for the mechanical response of sand (at different levels of saturation with water) under shock-loading conditions generated by researchers at Cavendish [Bragov AM, Lomunov AK, Sergeichev IV, Tsembelis K, Proud WG. The determination of physicomechanical properties of soft soils from medium to high strain rates, November 2005, in preparation; Chapman DJ, Tsembelis K, Proud WG. The behavior of water saturated sand under shock-loading. In: Proceedings of the 2006 SEM annual conference and exposition on experimental and applied mechanics, vol. 2, 2006.p.834–40] are used to parameterize our recently developed material model for sand [Grujicic M, Pandurangan B, Cheeseman B. The effect of degree of saturation of sand on detonation phenomena associated with shallow-buried and ground-laid mines. J Shock Vib 2006;13:41–61]. The model was incorporated into a general-purpose non-linear dynamics simulation program to carry out a number of simulation analyses pertaining to the detonation of a landmine buried in sand and to the interactions of the detonation products, mine fragments and sand ejecta with various targets. A comparison of the computed results with their experimental counterparts revealed a somewhat improved agreement with the experimental results in the case of the present model as compared to the agreement between the widely used porous-material/compaction model for sand and the experiments.

Keywords: Sand; Material model; Detonation; Shallow-buried mine; Blast loading

1. Introduction

Recent advances in numerical analysis capabilities, particularly the coupling of Eulerian solvers (used to model gaseous detonation products and air) and Lagrangian solvers (used to represent vehicles/platforms and soil), have allowed simulations to provide insight into complex loading created by the mine blast event. However, a quantified understanding of the blast phenomena and loadings through computer modeling is still not mature. As discussed in our previous work [3], the lack of maturity of computer simulations of the blast event is mainly due to inability of the currently available materials models to realistically represent the response of the materials involved under high deformation, high-deformation rate, high-temperature conditions, and the type of conditions accompanying landmine detonation.

The knowledge of the mechanical response of sand (or soil in general) under shock/blast loading conditions is critical in many engineering disciplines and commercial and military endeavors (e.g. mining, construction, design of survivable armored vehicles, etc.). For many years, the common practice was to develop purely empirical relations for soil at a given site using a variety of (non-standardized) experimental tests. Such relations are often found to have very little portability and may, when used in soil and test conditions different from the original ones, lead to widely different and unrealistic predictions [4,5]. To overcome these severe limitations, over the last dozen years general researchers have attempted to develop a constitutive material model for sand, which could include various

*Corresponding author. Tel.: +1 864 656 5639; fax: +1 864 656 4435.
E-mail address: mica.grujicic@ces.clemson.edu (M. Grujicic).

0267-7261/$ - see front matter
doi:10.1016/j.soildyn.2007.05.001

Nomenclature

α	porosity
β	saturation ratio
C	speed of sound
e	internal energy
η	compression ratio
Γ	Gruneisen gamma
P	pressure
φ	yield stress to pressure proportionality coefficient
ρ	density
s	slope of $U_s - U_p$ relationship
σ	yield stress
V	volume
x	spatial coordinate
y	spatial coordinate

Subscripts

Bulk	bulk material quantity
Comp	value at full compaction
dry	dry sand quantity
fail	failure-related quantity
H	Hugoniot quantity
MC	Mohr–Coulomb value
0	initial value
p	pore-related quantity
ref	fully compacted sand-related quantity
sat	saturation related quantity
Unsat	unsaturated sand-related quantity
w	water-related quantity

aspects of sand composition/microstructure and the moisture and organic matter contents (e.g. [1–5]).

Sand has generally a complex structure consisting of mineral solid particles, which form a skeleton. The pores between the solid particles are filled with a low-moisture air (this type of sand is generally referred to as "dry sand"), with water containing a small fraction of air ("saturated sand") or comparable amounts of water and air ("unsaturated sand"). The relative volume fractions of the three constituent materials in the sand (the solid mineral particles, water and air) are generally quantified by the porosity, α, and the degree of saturation (saturation ratio), β, which are, respectively, defined as

$$\alpha = \frac{V_p}{V} \tag{1}$$

and

$$\beta = \frac{V_w}{V_p}, \tag{2}$$

where V_p is the volume of void (pores), V_w is the volume of water and V is the total volume.

Surface roughness and the presence of inorganic/organic binders are generally considered to be the main causes for friction/adhesion at the inter-particle contacting surfaces. Deformation of the sand is generally believed to involve two main basic mechanisms [4,5]: (a) elastic deformations (at low-pressure levels) and fracture (at high-pressure levels) of the inter-particle bonds and (b) elastic and plastic deformations of the three constituent materials in the sand. The relative contributions of these two deformation mechanisms as well as their behavior are affected primarily by the degree of saturation of sand and the deformation rate. Specifically, in dry sand, the first mechanism controls the sand deformation at low pressures while the second mechanism is dominant at high pressures and the effect of deformation rate is of a second order. In sharp contrast, in saturated sand, very low inter-particle friction diminishes the role of the first deformation mechanism. On the other hand, the rate of deformation plays an important role. At low deformation rates (of the order of $1.0 \times 10^{-3}\,\mathrm{s}^{-1}$), the water/air residing in the sand pores is squeezed out during deformation and, consequently, the deformation of the sand is controlled by the deformation of the solid mineral particles. At high deformation rates (of the order of $1.0 \times 10^{5}\,\mathrm{s}^{-1}$) and pressures (of the order of ca. 1 GPa), on the other hand, water/air is trapped within the sand pores and the deformation of the sand is controlled by the deformation and the volume fractions of each of the three constituent phases.

In the areas of soil mechanics and soil dynamics, it is often assumed that the solid particles do not undergo plastic deformation and that the water phase is incompressible. The external loading is internally supported by the soil skeleton (via the so-called "effective stress" and by the water (via the so-called "pore pressure") [6]. Furthermore, the deformation of soil is controlled by the effective stress since the water and gas do not support any shear loading and are capable of flowing out through the soil pores. A number of investigators (e.g. [4,5]) clearly established that the effective stress approach discussed above is correct under the static/quasi-static loading conditions but it becomes deficient under shock-loading conditions. The two key deficiencies of the effective stress approach are the inability to account for: (a) deformation of the solid particles under shock loads and (b) the fact that due to a very short duration of shock loading, water may become trapped in soil pores and provide additional load support.

To overcome these limitations of the effective stress approach, Wang et al. [4,5], proposed a so-called "three-phase soil model". The model includes an *Equation of State* (based on the conceptual approach developed by Henrych [7]), a Drucker–Prager type strength model [8] and a damage model for degradation of strength and stiffness of the soil skeleton. Despite its solid physical foundation, the three-phase model was not widely accepted in the