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The Mach stem phenomenon for shaped obstacles buried in soil

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ABSTRACT

The paper investigates the explosion characteristics of a below ground event of an explosive charge in proximity to a rigid cylindrical obstacle. The two-dimensional study simulates a line explosive and a parallel long cylindrical structure. The investigation shows that the unloading branch has a negligible effect on the peak pressure envelope whereas shear behavior and explosives burning have a considerable effect and should not be disregarded. The effect of the soil's equation of state and especially the full locking parameter on the pressure distribution on an obstacle has been studied. At a short standoff distance where a steep pressure growth beyond the full compaction point is developed, the pressure distributions envelope shows three maxima values that are located at some distance away from the axis of symmetry. It is different than the common single peak along the axis, in the case of a distant explosion. This effect is more pronounced for a medium having sharper pressure growth in the EOS beyond the full compaction point and for smaller charge standoff distances. The pressure distributions analysis indicates that the appearance of second (absolute-primary) and third (secondary) peaks are caused by the Mach stem effect appearing in a soil medium with full locking. The secondary peak pressure envelope maximum corresponds to the secondary Mach stem phenomenon that does not appear in the case of a planar wall, where the incident angle depends on the wave front curvature only.

1. Introduction

The problem of an underground explosion near a buried structure is of much interest and of great complexity [1–3]. It combines the shock wave propagation and its interaction with a buried structure, as well as the accompanied rather large soil deformations and the formation of an explosive cavity in soil [4,5] and the structures dynamic response. The shock wave propagation in soil is rather complex, and should follow on a highly nonlinear constitutive model [4,6,7]. Commonly rather simple models are used to represent the soil medium behavior, such as elastic [8,9] or elastic plastic with elastic volumetric deformation [10–12]. However, proper representation of the soil behavior should account for the bulk irreversible compaction [6,13]. When the explosive source is placed at a large distance from the buried structure, the incident shock wave action on the structure may be approximated by a plane wave [14]. For this simple case an analytical solution may be provided [1,5]. When the explosive is placed closer to the structure, the incident wave front must be considered as a spherical or a cylindrical wave, depending on the explosive's and the problem's geometry [15,16] and when the explosive is placed very close to the structure the interaction of the explosive cavity with the obstacle (i.e. the shock wave front distortion) must be taken into account [17,18]. The interaction problems of soils and structures are commonly solved by utilizing numerical methods such as finite element [9–11], finite difference [19], finite volumes [20], variational difference [21] and various coupled methods [12–22,23].

In earlier studies [17,18] the authors presented the variational difference method and its application to the analysis of an explosion in an infinite medium [18] and inside a buried lined cavity [17]. In recent works [24,25] this approach was implemented to analyze a deeply buried explosion of cylindrical charges in a compressible elastic plastic soil that occurs in proximity to a vertical rigid wall and found that when the explosion is relatively close to the wall, the envelope of the pressure distributions (connecting the maximum stress values of the pressure distributions at all times) shows a maximum value that is located at some distance away from the plane of symmetry and not along the plane of symmetry as is commonly the case in a distant explosion. It has been sown that this phenomenon is caused by the Mach stem effect appearing in a soil medium with significant hardening. The present paper considerably extends the investigation of [24,25] to shaped obstacles and is based on the original conference paper [26].

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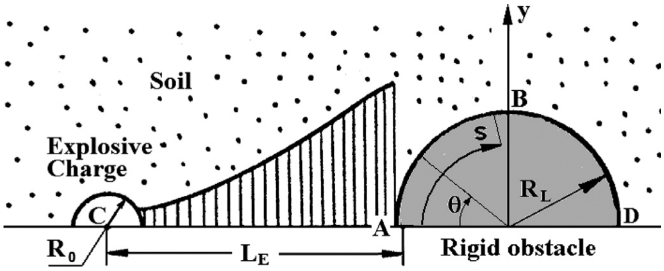

Fig. 1. The problem.

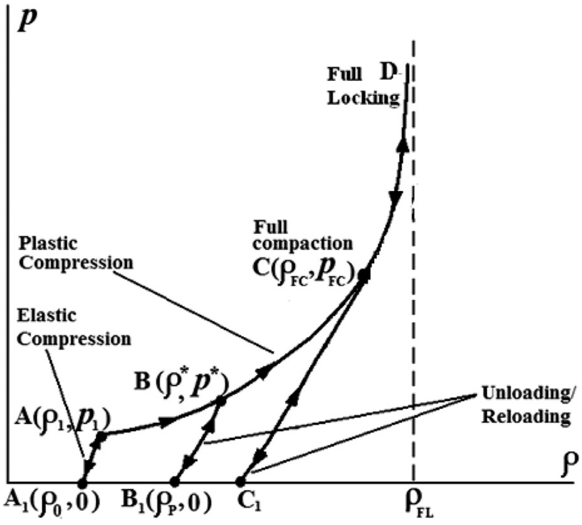

Fig. 2. Pressure–density relationship.

2. The model

Consider a line-charge explosion near a shaped (circular cross section) rigid obstacle (Fig. 1) that is buried in a homogeneous isotropic irreversibly compressible soil medium.

The pressure–density relationship is schematically shown in Fig. 2. The bulk behavior of this material starts with a linear elastic segment (A_1A) that is small and generally can be disregarded, especially when high pressures are considered. This elastic segment is followed by a zone of elastic plastic bulk compaction (segment *ABC*) with stiffening caused by the closure of the internal pores. A linear or non-linear elastic model (segments B_1B, C_1C) ABC represents unloading and reloading at this stage. The unloading line is uniquely determined by the maximum soil density ρ^* that is attained in the process of active loading. This irreversible process occurs as long as the density is smaller than the full compaction value ρ_{FC} (point *C*) corresponding to the full closure of the internal pores. Thereafter the pressure varies with the density according to a non-linear elastic behavior (segment *CD*). This zone corresponds to a constant ρ^* equal to a full compaction density and therefore during the entire process $\rho_1 \le \rho^* \le \rho_{FC}$. The model allows describing the range of pressure values from low pressures (for the case of a far explosion) to very high pressures (for the case of a nearby explosion).

The soil pressure–density relationship takes the form (see Fig. 2):

$$p = f(\rho,\ \rho^*) = \begin{cases} f_L(\rho) & \text{for the active loading } \ (\mathrm{A_1ABCD}) \\ f_U(\rho,\ \rho^*) & \text{for unloading and reloading } (\mathrm{B_1B},\ \mathrm{C_1C}) \end{cases} \quad (1)$$

where ρ is the soil current density.

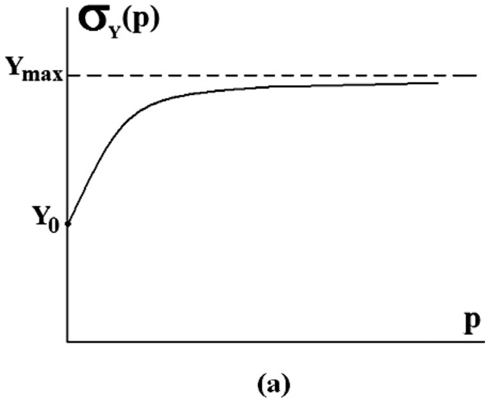

Fig. 3. Yield stress–pressure relationship.

The functions f_L and f_U of Eq. (1) depend on the type of the soil and may be obtained from dynamic compression tests.

The paper examines the medium having a full locking branch (*C-D*) with the following functions of equation of state [24]:

$$\begin{aligned} & f_L(\rho) = \rho_0 c_0^2 \frac{\varepsilon_V}{(1-\beta\varepsilon_V)^2}; \\ & f_U(\rho,\ \rho^*) = f_L(\rho^*) + c_U^2(\rho^*)(\rho-\rho^*); \\ & c_U(\rho^*) = c_{FC} + \frac{\rho_{FC}-\rho^*}{\rho_{FC}-\rho_0}(c_0 - c_{FC}) \end{aligned} \quad (2)$$

Here ρ_0 and c_0 are the initial density and sound velocity, $\varepsilon_V = 1-\rho_0/\rho$ is the bulk strain ($0 \le \varepsilon_V < 1/\beta$), c_0 is an initial sound velocity, $1/\beta$ is a full locking bulk strain (Fig. 2), $c_U(\rho^*)$ is the current sound velocity and $c_{FC} = \sqrt{df_L(\rho)/d\rho|_{\rho=\rho_{FC}}}$ is the sound velocity at the state of full compaction. The model assumes that the soil has no tensile resistance. Therefore, if during unloading from a compression state of stress the soil density reaches a permanent density ρ_p (Fig. 2), that corresponds to a zero hydrostatic stress, a discontinuity in the soil occurs and all the stresses (both spherical and deviatoric components) drop to zero. This type of equation of state is typical for soils with high level of bulk hardening at for high pressures (such as clay or clay loam) [4,16,18,23,24].

The Lundborg model [18] is used to describe the yield condition (see Fig. 3):

$$S_{ij}S_{ij} = \frac{2}{3}\sigma_Y^2(p);\ \sigma_Y(p) = Y_0 + \mu_Y p/(1+\mu_Y p/(Y_{\max}-Y_0)) \quad (3)$$

where Y_0 is the shear cohesion, μ_Y is an internal friction coefficient and $Y_{\max}$ is the shear strength.

The calculations have been performed using either a home-made program that is described in detail in [18,24] and the commercial software AUTODYN-13. Both programs show similar results.

3. The charge explosion in proximity to cylindrical obstacle

Consider the response of a rigid cylindrical obstacle of radius $R_L = 0.5$ m (Fig. 1). The obstacle is buried in soil and subjected to an external explosion of a line TNT charge of radius $R_0 = 10$ cm that is placed at a depth of $H = 3.6$ m below the soil top surface, and at a distance L_E from the lining front (point A, Fig. 1). Note, that both the obstacle and the charge are buried deep enough in the soil to avoid any free surface effects including the free surface cratering.

A recent study [25] examined the peak pressure distribution for both planar and cylindrical obstacles (peak pressure envelop). It shows that for a nearby explosion the maximum value of the peak pressure envelope is developed somewhat away from the plane of