International Journal of Impact Engineering 106 (2017) 30–43

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Resistance of a concrete target to penetration of a rigid projectile - revisited

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ARTICLE INFO

Article History:
Received 29 October 2016
Revised 17 February 2017
Accepted 18 February 2017
Available online 16 March 2017

Keywords:
Concrete penetration models
Material properties
Equation of state
Advanced material testing

ABSTRACT

Penetration into concrete is a subject of much interest and importance that attracts researchers for many years. This paper aims at reviewing the major contributions to model the deep penetration of a rigid projectile that perpendicularly hits a concrete target with emphasis on concrete target resistance. With regard to the concrete target resistance there exist four major modeling families: empirical, semi-empirical, analytical and theoretically based computational models. The paper overviews representative models and shows what target resistance parameters are used in these models and discusses some inherent weaknesses. The paper mainly refers to the dependence of concrete target resistance on the material characteristics; the concrete unconfined strength clearly appears to be the major identifier of the target resistance in these models. In many expressions the penetration depth is inversely proportional to the square root of the unconfined strength. The paper debates with this formulation which correlates the target resistance with the unconfined compression strength through a smooth continuous function of the strength disregarding the effect of different concrete mix designs that produce the same unconfined strength. Our own experimental studies are described to prove that concrete targets of similar unconfined strength demonstrate different resistance and damage depending on the different concrete compositions.

Attention is given to the comprehensive description of target resistance via the equation of state and the failure envelope; this material behavior presentation is common in computational models, and is also adopted, although in a very simplified form, in analytical models. However, it will be shown that these advanced models are also commonly identified through the unconfined strength, and therefore they poorly describe the specific characteristics of the material under discussion. There is a need to produce refined data for the equation of state and of the failure envelope that are related to the concrete mix characteristics. Recently a new wide scope testing program has been initiated at our laboratory to achieve that goal, and early results have already been produced.

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http://dx.doi.org/10.1016/j.ijimpeng.2017.02.021

1. Introduction

Penetration into concrete is a subject of much interest and of great complexity. For many decades much research has been conducted in an attempt to enhance our understanding of this problem and develop calculation tools to analyze the projectile motion into the concrete target and to estimate the target response. It aims at providing improved calculation tools for detailed exhaustive analysis of the projectile-concrete interaction as well as simple penetration formulae for quick assessment of a projectile's final depth of penetration into a thick target [1–3].

In general, interest is given to two major related problems: the first problem is penetration into a sufficiently thick target, where the projectile velocity decreases until full penetration is reached at a depth that is considerably smaller than the target thickness such that no rear face effects are observed; the second problem is penetration into a moderately thick or a relatively thin target where scabbing damage or shear plugging are observed on the rear side of the target, while the projectile is either stopped within the target or perforates the target with a residual velocity. These two related problems have much in common but they are considerably different as well. This paper will focus mainly on the first problem of penetration into a sufficiently thick target although will refer to several aspects of the second problem.

As a result of the research efforts, different methods have been developed and enhanced concrete based protection solutions were proposed. These studies also developed the understanding of penetration mechanics into concrete and provided insight into the interaction between a projectile and the surrounding concrete. Nevertheless, concrete penetration is a very complex problem and mechanical processes involved are far from being fully understood. There exist different methods to analyze penetration into concrete.

These methods may be classified according to different criteria. In this paper the different methods will be classified according to the target resistance representation and its incorporation in the modeling. It should be noted that the present review aims at discussing the target resistance aspects and will refrain from detailed presentation of the different models and from discussing their solution procedures.

Empirical formulae and semi-empirical methods are the simplest expressions; they aim at providing limited information, mainly towards estimating the full penetration depth, and they may not provide any information on the target response and on the target interaction with the projectile.

The computational methods using hydro-codes on the other hand are the most difficult to use and consume large computer and time resources however they provide detailed information on the penetration event. Computational methods and numerical solutions is a general title to many different formulations and techniques, some of which formulate the full interaction between the projectile and the target at all times and their outputs include the projectile motion and the target response, the developing cavity shape around the projectile and the pressures acting on the projectile that result from its interaction with the target. Other numerical solutions combine analytical and numerical approaches and may adopt different assumptions for simplification, focus on the projectile motion disregarding the target response etc. In this paper aiming at discussing the target resistance parameters in the material modeling, the different computational models will not be reviewed; from the target resistance point of view computational analysis whatever it is may adopt any material model of any degree of complexity and use any available identifiers of target resistance and the distinction between the different models that may include different numerical solution techniques is not related to the subject matter of target resistance aspects in the modeling.

Analytical methods are a light version of the latter and attempt to provide a simplified theoretically based approach with the ability to calculate much information on the penetration event although being based on simplifying assumptions. Due to their simplifying formulation the analytical models may be fully or partially derived analytically. All these approaches require data on the projectile geometry, its mass and impact velocity and on the target geometry and its mechanical properties. Many of the computational methods require representation of the projectile-target interaction and the analytical methods require making assumptions on that regard. These assumptions are a key point that is not easy to fulfil properly and may require simplifications that may affect the entire model and its accuracy.

Most of the required data to define the problem (e.g. projectile geometry and mechanical properties, target geometry etc.) are easy to provide, however concrete resistance that is a key parameter is difficult to determine and it is introduced into the analysis in different ways. Numerous assumptions are involved in the analysis of a penetration problem in an attempt to achieve an acceptable solution. This paper aims at reviewing the different major modeling approaches with emphasis on the target resistance representation in the materials models being used. The paper aims at assessing their suitability for deep penetration analysis. With regard to the concrete resistance, one of the myths is the direct relationship between concrete resistance to penetration and its uniaxial (or unconfined) compression strength. This issue will be examined and refuted in the following.

Concrete is a rather complex material and its behavior is under continuous investigation. Much knowledge has been gained regarding the chemical, physical and mechanical behavior of concrete and its ingredients in a wide range from the microscopic to the macroscopic levels. Many different test methods were developed, some of them (such as the uniaxial compressive strength test) are simple and implemented in any standard testing laboratory while some others are rather complex (such as multi-axial high pressure tests), that require special expensive custom made setups that exist in a limited number of laboratories.

In structural analysis where reinforced concrete (RC) is widely used, concrete is commonly identified by its uniaxial (unconfined) compressive strength. This is almost the sole identification, from which all other necessary concrete parameters for the structural analysis may be drawn, such as its tensile strength, Young's modulus etc. The uniaxial compressive strength is obtained from standard laboratory tests that are conducted on standard specimens (cubes or cylinders of specified geometry, depending on the national standard) that are prepared and cured in a specified way. As the cement continuously reacts with the residual water in the concrete in a process of hydration and continues to further gain some extra strength with time, it is commonly accepted that the standard strength is determined in tests on 28 days old specimens. At this age concrete may be considered sufficiently mature where it reaches about 90% of the maximum possible strength in common normal strength concrete (NSC). The standardized strength definition allows strengths comparisons of different concrete castings, from different batches that may be tested by different standard testing laboratories. This may be quite satisfying for RC structures made of NSC, where in most cases