TARGET HARDNESS COMPARISONS WITH THE IAEA UNYIELDING TARGET*

A. GONZALES, J.D. PIERCE
Sandia National Laboratories,
Albuquerque, New Mexico

D.R. STENBERG
Southwest Engineering Associates,
El Paso, Texas

United States of America

Presented by G.C. Allen, Jr.

Abstract

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Various types of targets were compared with respect to their hardness upon a cask-type object. A cylindrically shaped unit was impacted into soil, concrete and rigid targets at velocities ranging from 13 m/s (44 ft/s) to 27 m/s (88 ft/s). Experimental and analytical results were compared to better understand the responses generated by different targets to a projectile.

INTRODUCTION

Sandia National Laboratories is conducting an ongoing evaluation that seeks to relate more realistic yielding targets to an unyielding target, as defined in the International Atomic Energy Agency's Safety Series No. 37 [1]. This evaluation includes experimental testing and analytical calculations to compare effects of various targets on the impact of a simple model transportation cask. Two types of materials were chosen to represent yielding targets: soil and concrete. Native in situ desert soil found in the Albuquerque, New Mexico, area represented the soil target. Typical United States Federal Highway cross-sections and Federal Aviation Administration (FAA) airport runway cross-sections were used for the concrete targets. Examination of cask responses at various impact velocities onto yielding targets was made and compared with the 9 m drop onto an essentially unyielding target.

The model transportation cask used in this study was a 2500 kg (5500 lb) steel cylinder without energy-mitigating devices or impact limiters attached. This blunt-shaped model approximates a half-scale truck transportation cask shown in Fig. 1. Analytical calculations concentrated on trying to account for soil and concrete

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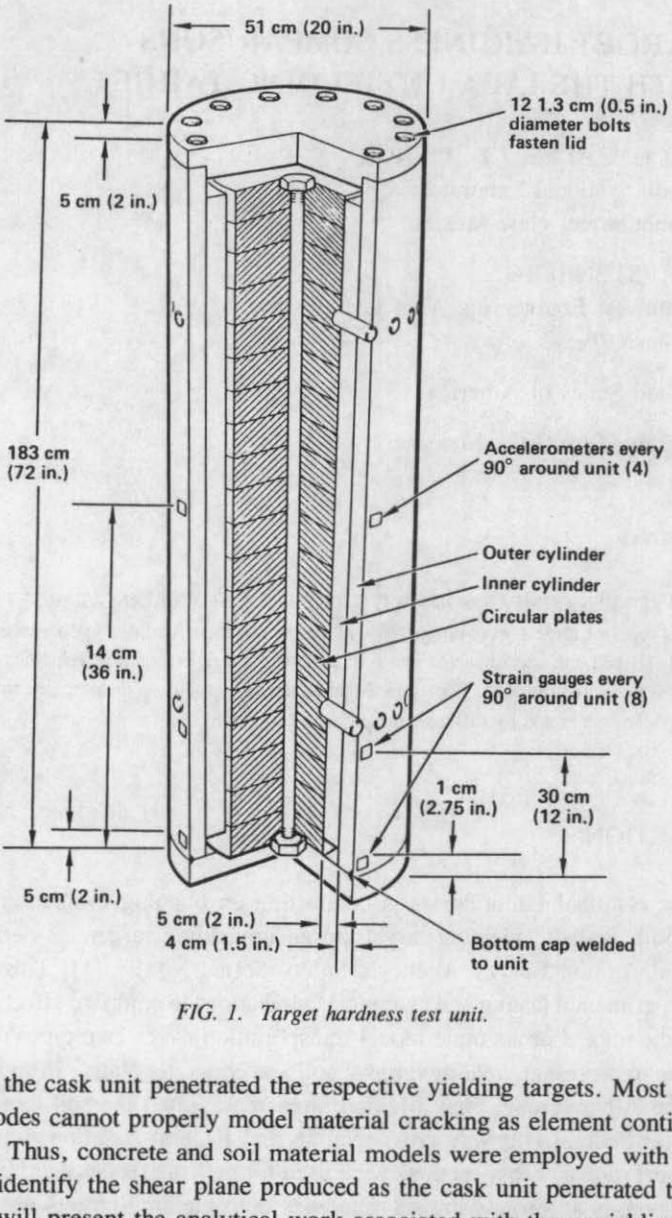

FIG. 1. Target hardness test unit.

cracking as the cask unit penetrated the respective yielding targets. Most analytical computer codes cannot properly model material cracking as element continuity will be violated. Thus, concrete and soil material models were employed with slidelines in order to identify the shear plane produced as the cask unit penetrated the target. This paper will present the analytical work associated with the unyielding and soil targets.

TARGETS

Four types of targets were used in this evaluation: desert soil, concrete airport runway, concrete highway and an essentially unyielding target. They provide a range of impact stiffnesses and include targets common to everyday life. A soil target was not constructed to meet particular material property specifications. Instead, native in situ desert soil found at the test site was characterized.

The unyielding surface is a 56 metric tonne (62 ton), steel-faced concrete target located at the Coyote Test Site in Albuquerque, New Mexico. The $3 \times 3 \times 0.13$ m ($10 \times 10 \times 0.42$ ft) steel plate is integrally fastened atop a 7 m (22 ft) diameter, 3.6 m (12 ft) deep concrete mass. To aid in fastening the steel plate to the concrete, there are 30 steel tubes welded to the bottom of the plate. These tubes efficiently spread the load into the concrete. This target has been used extensively for a variety of 9 m drops and 1 m puncture tests since 1975.

Three 6×6 m (20×20 ft) concrete slabs were constructed according to FAA design criteria to represent the concrete runway targets. The compacted soil beneath the 46 cm concrete slabs underwent a series of plate-bearing tests to assure proper soil strength and density. Included in the runway slabs is a 13×13 cm (5×5 in) mesh steel reinforcement to provide strength in tension and shear. Several cylinders and cores were laboratory tested to assure the concrete obtained a compressive strength of 34 MPa (5000 lbf/in^2).

Using applicable Federal Highway design criteria, three 3×3 m (10×10 ft) concrete slabs were constructed to represent the highway targets. The native soil, compacted to 95% of its optimum density [2], constituted the Class IV sub-base. Crushed quarry stone compacted to 95% of its optimum density, and satisfying Federal Highway [3] specifications, represented the Class II base. A 21 MPa (3700 lbf/in^2) minimum compressive strength concrete, 23 cm (9 in) thick, provided the roadway surface.

A reinforcing bar was not included in the roadway design for two reasons. First, the results of highway rehabilitation projects in the USA have shown that steel reinforcing bars greatly increase the difficulty in replacing roadway sections. Thus, typical highway designs are now omitting reinforcing bars in order to facilitate highway maintenance and rehabilitation efforts. The second reason stems from an analytical perspective. Since analytical codes do not fully duplicate the response of concrete under large impact loadings, the addition of reinforcing bars would further complicate the analysis. Thus, it was decided to avoid a variable that would increase the difficulty of the problem without providing any additional benefits.

Determining a suitable soil target presented several problems. Since soil properties and characteristics can change drastically from area to area, finding a typical soil section proved to be impractical. Thus, the native soil at the test facility was used for the soil targets. The soil was not altered by compacting or adding moisture. Instead, considerable effort was made to fully characterize all of the soil properties. A series of laboratory and on-site tests performed through the University of New Mexico defined the soil properties [4]. The tests include compaction, confined compression, and consolidation. The soil through 183 cm (72 in) exhibited various differences in properties. This variation of properties illustrates the complexity of characterizing soil both experimentally and analytically. Considerable effort was made to provide yielding targets that were representative of an environment which exists in real life. In addition, these targets needed to be reproducible either in construction or by characterization.

TESTING

The test programme consisted of a series of drops onto the various targets in order to determine target hardness effects. The tests included three drops on soil, at 13 m/s, 20 m/s and 27 m/s; two drops on concrete highway at 13 m/s and 27 m/s; two drops on concrete runway at 13 m/s and 20 m/s and a 13 m/s drop onto the unyielding target.

The test unit shown in Fig. 1 represents the approximate geometry and mass of a half-scale truck transportation cask. The unit consists of outer and inner cylinders which are bolted together, representing a cask outer container and liner, respectively. To increase the mass, circular plates fill the unit in order to model the cask contents. The top cap is welded to the outer cylinder and the top lid is fastened via twelve 1.3 cm (0.5 in) diameter bolts. The entire unit is made of an A36 mild carbon steel.

The instrumentation for each unit included eight strain gauges and four accelerometers (see Fig. 1). Strain gauges, one every 90° around the unit, were situated at two levels, 7 cm (2.75 in) and 30 cm (12 in) from the bottom. Accelerometers, also placed every 90° around the unit, were mounted at the midplane. Each unit underwent geometrical inspection for length, diameter and circumference before and after each test to monitor unit deformations. Also, photometrics, ranging in camera speed from real time to 2000 frames/s, were employed for velocity measurements and event recording. Test data included strain, acceleration, deformation, impact velocity and penetration of the target. This information was compared with experimental results and analytical calculations.

The test apparatus consisted of a 23 m (75 ft) I-beam attached to a frame. The I-beam helped guide the unit via a sled toward the target. This apparatus permitted the use of jet rockets to obtain higher impact velocities, in addition to keeping the unit perpendicular as it fell toward the target. Upon reaching the lower section of the I-beam, the test unit would be separated from the guide sled and would impact, unrestrained, onto the target.

TEST RESULTS

The test series produced the strain results shown in Table I. Only the 13 m/s (44 ft/s) impact velocity onto the unyielding target produced any permanent cask deformations. This impact velocity equates to a 9 m free drop. The strain gauges indicated that the impact produced a compression of 1000 microstrains; however, the outer cylinder began to stretch or bow out and thus final deformation strain was

TABLE I. TARGET HARDNESS TEST RESULTS

Target	Impact velocity m/s (ft/s)	Unit penetration cm (in)	Maximum compressive strain (microstrains)
Soil	13 (44)	48 (19)	90
	20 (66)	64 (25)	600
	27 (88)	86 (34)	900
Concrete runway	13 (44)	0.6 (0.25)	500
	20 (66)	10 (4)	1500
Concrete highway	13 (44)	10 (4)	400
	27 (88)	48 (19)	1500
Unyielding target	13 (44)	0	3500[a]

[a] Final strain in tension.

3500 microstrains in tension. This is more than a factor of two over any of the strains resulting from impacts on the other targets at greater velocities.

Reviewing the strains experienced from impacts on the soil and concrete targets shows a noticeable increase in strain readings as the impact velocity increases. The kinetic energy available for deforming the test unit is directly related to the square of the impact velocity. However, except for the concrete highway targets, the increase in strain on the test unit from a 13 m/s (44 ft/s) impact velocity to higher values was disproportionately higher than a square term. Thus, the correlation between increased impact velocity and expected strains is complicated by changes in the energy partitioning that occurs as the impact velocity increases. However, for this particular evaluation, the unyielding target did cover the worst case.

COMPUTER ANALYSIS

The major uncertainty in the computer analysis centred on proper accounting for shearing and cracking within the yielding targets of soil and concrete. Sufficient data and test results exist to properly model the response of an object striking a rigid, unyielding target. However, the analytical modelling is quite different with respect to a massive blunt-end unit impacting concrete or soil to produce widespread yielding

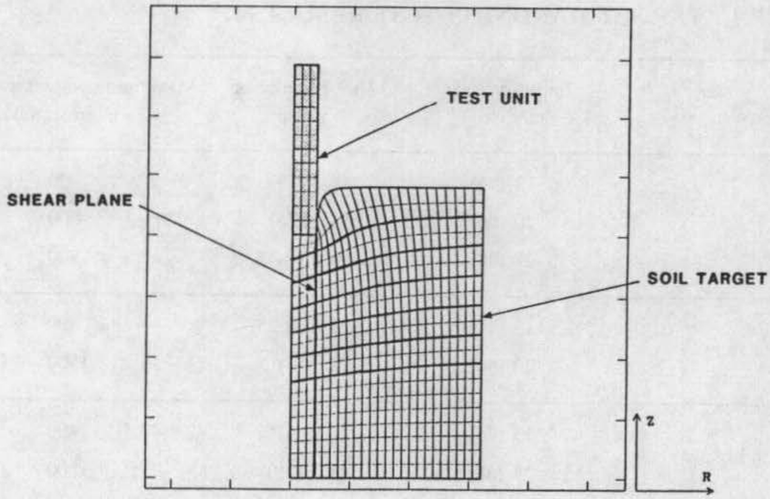

FIG. 2. Finite element model for soil impact analysis.

of the target. The analysis of the soil and the unyielding analysis are discussed further in this section.

Laboratory testing to determine soil properties resulted in a soil cross-section consisting of six different layers. These layers were modelled, as shown in Fig. 2. In addition, a shear line was introduced into the finite element mesh so as to properly model the shear surface produced as the unit penetrates into the target. Experimental tests show that this phenomenon does occur. The analysis was performed using the DYNA2D [5] and PRONTO [6] finite element codes, with the results shown in Table II.

PRONTO calculations yielded penetration values with much better consistency than DYNA2D, the results matching well with experimental data, though the analytical procedures were complex and detailed. All of the soil properties were required for the analysis and some fine tuning of the data was required to get such good agreement. Note that if a different type of soil was used, the analytical and experimental values would change dramatically.

Impact on the unyielding target was analysed using DYNA2D, an explicit finite element code. The results matched closely with the experimental data obtained. A conservative acceleration of 1600g analytically approximates the 1400g experienced by the unit during the 13 m/s (44 ft/s) impact. The axial stresses at the point of the first set of strain gauges, 7 cm (2.75 in) above the point of impact, were calculated at 24.8 MPa (36 000 lbf/in^2) versus 25.8 MPa (36 700 lbf/in^2) obtained experimentally. The unit material has a yield stress of 24.8 MPa (36 000 lbf/in^2). This further

TABLE II. COMPARISON OF ANALYTICAL AND EXPERIMENTAL TEST UNIT PENETRATION RESULTS FOR A SOIL TARGET

Impact velocity m/s (ft/s)	DYNA2D cm (in)	PRONTO cm (in)	Experimental cm (in)
13 (44)	50 (20)	41 (16)	48 (19)
20 (66)	84 (33)	64 (25)	64 (25)
27 (88)	119 (47)	89 (35)	86 (34)

illustrates the advantage of analysing and experimenting using a rigid, unyielding surface. The results are repeatable and verifiable.

SUMMARY

A cask-type cylindrical mass was impacted into a variety of targets at several velocities. For the targets and velocities used, an unyielding target produced the maximum damage to the test unit. With respect to the regulatory 9 m drop onto an unyielding target, the test data were easily duplicated via computer analysis, though penetration into the soil targets proved quite difficult to analyse. This included the effort of trying to fully characterize the soil and using complex analytical methods to account for cracking, spalling and shear plane formation during impact. The advantage of a rigid, unyielding target was quite evident in duplicating the results found from analysis and testing.

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