Research Plan for ECM Required Earth Cover

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Abstract

The U.S. Army has a large number of earth-covered magazines (ECMs) for storing ammunition and explosives. These ECMs are generally sited for a maximum of 250,000- or 500,000-lb net explosive weight and designed to have a minimum of 2 ft of earth cover as specified in DoD 6055.09-M. Over time, the earth cover may erode or settle resulting in an earth cover that is less than 2 ft thick. In accordance with DoD 6055.09-M, the ECM must then be sited as an above-ground magazine (AGM) impacting quantity-distance requirements and resulting in lower explosive quantities that can be stored in the ECM. It is not clear that this requirement is realistic. To address this issue, the U.S. Army Technical Center for Explosives Safety requested support from the U.S. Army Engineering and Support Center, Huntsville and the U.S. Army Engineer Research and Development Center to address the issue of the effect of varying earth covers for ECMs. Of interest is the point at which an ECM behaves as an AGM, from the perspective of a donor of and an acceptor for explosive loading. This paper presents the initial series of experiments that will be conducted at ¼ scale to begin to evaluate the effect on ECM loading due to varying earth cover thickness.

Introduction

The U.S. Department of Defense (DoD) has a very large number of earth-covered magazines (ECMs) for storing ammunition and explosives. The majority of these earth-covered magazines are arch-type structures with widths of 26.5 ft and lengths varying from 40 ft to 80 ft. These magazines are generally sited for a maximum of 250,000- or 500,000-lb net explosive weight (NEW) and are designed to have a minimum of 2 ft of earth cover as specified in DoD 6055.09-M, *DoD Ammunition and Explosives Safety Standards* [1]. Over time, the ECM earth cover may erode or settle, resulting in an earth cover that is somewhat less than 2 ft thick. In accordance with DoD 6055.09-M, paragraph V2.E5.5.3.2, the Earth-Covered Magazine must then be sited as an Above-Ground Magazine (AGM). This potentially impacts quantity-distance requirements, usually resulting in the need to lower the NEW stored in the magazine. The largest impact this has on siting is on the required inter-magazine distance (IMD). For example, with less than 2 ft of earth cover, the side-to-side exposure IMD would increase from K1.25 ($D = 1.25*NEW^{1/3}$) to K6 ($D = 6*NEW^{1/3}$). For 500,000-lb NEW, this would increase the IMD from 99 ft to 476 ft. Since the distance between existing magazines cannot be changed, the storage capacity in this case must be drastically reduced.

The origin of the 2 ft of earth cover requirement is not documented. The earliest known ECM designs (Army 652-686 & 652-693 from 1941 [2, 3] and Navy 357428-357430 from 1944 [4]) required a minimum of 2 ft of earth cover. However, no basis of design or calculations for these ECM designs have been found.

The following questions have been raised.

1. At what point does an ECM really behave like an AGM?

2. Is it possible that the quantity-distance requirements can be adjusted between the ECM requirements and the AGM requirements by some sort of equation dependent on the actual earth-cover thickness?

In order to address these issues, the U.S. Army Engineer Research and Development Center (ERDC) and the U.S. Army Engineering & Support Center, Huntsville (CEHNC) developed a series of experiments (code-named MERCURY) to investigate the effect of varying earth-cover thickness for ECMs. MERCURY is an acronym for Magazine EaRth Cover Update/Reassessment studY. Of particular interest to this effort is the point at which an ECM behaves as an AGM, both from the perspective of a donor and an acceptor for explosive loading. The initial test series is designed to determine the influence of soil cover thickness on the blast load distribution applied to an acceptor ECM structure from a nearby open-air detonation. Additional test series will further evaluate the effect of earth cover on the blast loads applied to an acceptor ECM and will also evaluate the effect of earth cover on the blast loads produced by a donor ECM. The goal of this testing effort is to provide sufficient data to justify updates to the current requirements such that influences from reduced soil cover can be accurately accounted for, thus eliminating the "sudden" transition from ECM to AGM requirements. These tests will also provide benchmark data for comparison to and validation of results from companion numerical simulations that ERDC has proposed as a means of augmenting the evaluation of the effect of ECM earth cover. This paper will focus on the initial series of experiments under this research effort.

Historical Earth-Covered Magazine Testing

Full-scale earth-covered magazine testing was performed at the Naval Proving Ground (NPG), Arco, Idaho, during October 1946. Two tests were performed with a 500,000-lb TNT detonation in a standard 80-ft-long ECM with 2 ft of earth cover. A third test was performed with a 250,000-lb TNT detonation in an 80-ft-long ECM with double (4 ft of) earth cover. These tests were designed to determine whether the side-to-side IMD could be reduced from 400 ft to 185 ft, and whether the maximum quantity in an ECM could be raised to 500,000 lb without incurring undue risk of propagation of explosion from one ECM to another. Both of these objectives were confirmed by the tests. These tests are detailed in Department of Defense Explosives Safety Board (DDESB) Technical Paper 5 (TP 5)[5].

Further ECM tests were performed at NPG at 1/10th scale [6] to determine the effects of increasing earth cover on the donor magazine. Acceptor magazines all had the full-scale equivalent of 2 ft of earth cover. The donor magazines were tested with the equivalent of 250,000 lb and 500,000 lb of TNT with equivalent full-scale earth covers of 2 ft, 7.5 ft, and 15 ft. The major conclusions (as stated) were (1) the scale model law holds for airblast, crater diameter, horizontal soil movement, and damage to structures caused by airblast, (2) the scale model law does not hold for crater depths, vertical soil movement, vertical component of ground shock or damage to target igloos (which is partly caused by ground shock), (3) increased earth cover reduces airblast and damage to target structures, (4) the use of standard service earth-covered igloos does not warrant halving the distance specified by the American Table of Distances for safety of inhabited buildings from unbarricaded charges, and (5) standard Army revetments around open charges do not reduce airblast generated by detonation of their contents. These tests are detailed in DDESB TP 4 [7].

Later tests, designated the Hastings and Navajo tests [8, 9], were performed using full-scale ECMs, but the NEWs were very small. The ESKIMO tests [10-17] were full- and scale-model tests with an equivalent earth cover of 2 ft. No historical tests were found using less than 2 ft (full-scale) of earth cover. Figure 1 shows the ESKIMO test matrix (as per A-P-T Research, Inc., presentation slide from ECM Summit, June 2017 [18]).

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ESKIMO

Event	Date	ECM Donor	ECM Acceptors	Type	Donor NEW (lbs)	Donor Charge
I	12/8/71	✓	✓	Arch	200,000	13,696 155mm projectiles
II	5/22/73		✓	Arch	24,000	72 M117 bombs--nominal hemisphere shape
III	6/12/74	✓	✓	Arch	374,406	916 M117 bombs
IV	9/1/75		✓	Arch	37,000	TNT blocks in hemisphere shape
V	8/17/77		✓	Arch	75,000	TNT blocks in hemisphere shape
VI*	7/23/80	✓	✓	Box	51,300	60 MK 16 torpedoes
VII-A**	9/5/85		✓	Box		Foam HEST loading on roof
VII-B***	9/12/85		✓	Box	13,616	TNT blocks in hemisphere shape

*1/2-scale donor magazine
**Foam HEST loading on roof
***Blast loading on door

Figure 1. ESKIMO test matrix slide from A-P-T Research, Inc. [18].

Experiment Design

As stated previously, this paper focuses on the initial series of experiments (MERCURY Series 1) under this research effort. This series will explore the use of ¼-scale testing to begin to evaluate the effect of earth-cover thickness on ECM acceptor loading. The ERDC has conducted numerous experiments at ¼ scale, and results have typically demonstrated good correlation to larger scale and full-scale events. A 1/4-scale experiment is considered an acceptable scale at which reinforced concrete structures, such as a true arch-shaped AGM, can be faithfully replicated with confidence. Past testing has shown the effect of gravity on airblast at this scale to be insignificant. Experiment NEWs will be the equivalent of 75,500-lb TNT (full scale), and the ESKIMO V full-scale test will be used as a scaling validation point for selected scale model tests. The experiment in this study used C4 as the explosive. For the purpose of establishing the C4 explosive mass, an equivalence of C4/TNT of 1.28 was utilized.

In order to isolate the acceptor response and ensure uniform applied blast loading, bare, hemispherical high explosive (HE) donor charges composed of C4 explosive placed on the ground surface will be used for this series. The proposed Series 1 experiment matrix is shown in Table 1. A soil backfill will be emplaced to provide a consistent, known material on, around, and beneath the acceptor ECM and in the area between the acceptor and the donor charge. For this initial series, the acceptor will be modeled as a rigid, smooth-wall steel pipe to simulate an arched ECM structure's size and shape. The goal is to capture the load on the structure as a function of variation in earth-cover thickness and not to focus on the structural response, since this will depend on the actual design of the ECM. For each event, the airblast will be measured over a scaled distance (K) of 2.0 to 11.0. Scaled distance is determined by the distance (in ft) divided by $\sqrt[3]{922 \times 1.28}$. Interface stress gauges will be utilized to capture the soil loads transmitted directly to the acceptor's surface.

Table 1. Experiments matrix for MERCURY Series 1.

Experiment	Acceptor ECM	Donor Charge Type	Donor Charge Weight (lb)	Charge Scaled Standoff (K)	Charge Standoff (ft)	Full-Scale Earth Cover (ft)	¼-Scale Earth Cover (ft)
M1	Rigid Simulated Arch (6ft Ø steel pipe)	Bare C4	922	3.67*	38.78	2	0.5
M2	Rigid Simulated Arch (6ft Ø steel pipe)	Bare C4	922	3.67* or 2	38.75 or 21.13	**	**
M3	Rigid Simulated Arch (6ft Ø steel pipe)	Bare C4	922	3.67* or 2	38.75 or 21.13	**	**
* Full Scale Eskimo V match ** Pending M1 results							

Testbed Design

The acceptor ECM will consist of a half-buried, rigid steel pipe to simulate an ECM structural shape based on the scaled dimensions of the full-scale ESKIMO V test. The pipe will have an outside diameter of 6 ft with a length and wall thickness of 20 ft and 0.5 in., respectively. A soil backfill will be emplaced to provide a consistent, known material on, around, and beneath the acceptor ECM. The soil utilized will be a clayey sand material which will adhere to the requirements for earth cover material listed in V2.E5.5.3.1 of the *DoD Ammunition and Explosives Safety Standards*. Quality control measurements of the soil moisture and density will be collected during the construction process to ensure the soil remains consistent throughout and the as-placed soil conditions are captured for future testing. Figure 2 shows plan and profile views of the testbed design. The ECM berm cover will have 2:1 side slopes; the model ECM will feature a steel headwall and wingwall on one end, as shown in Figure 3.

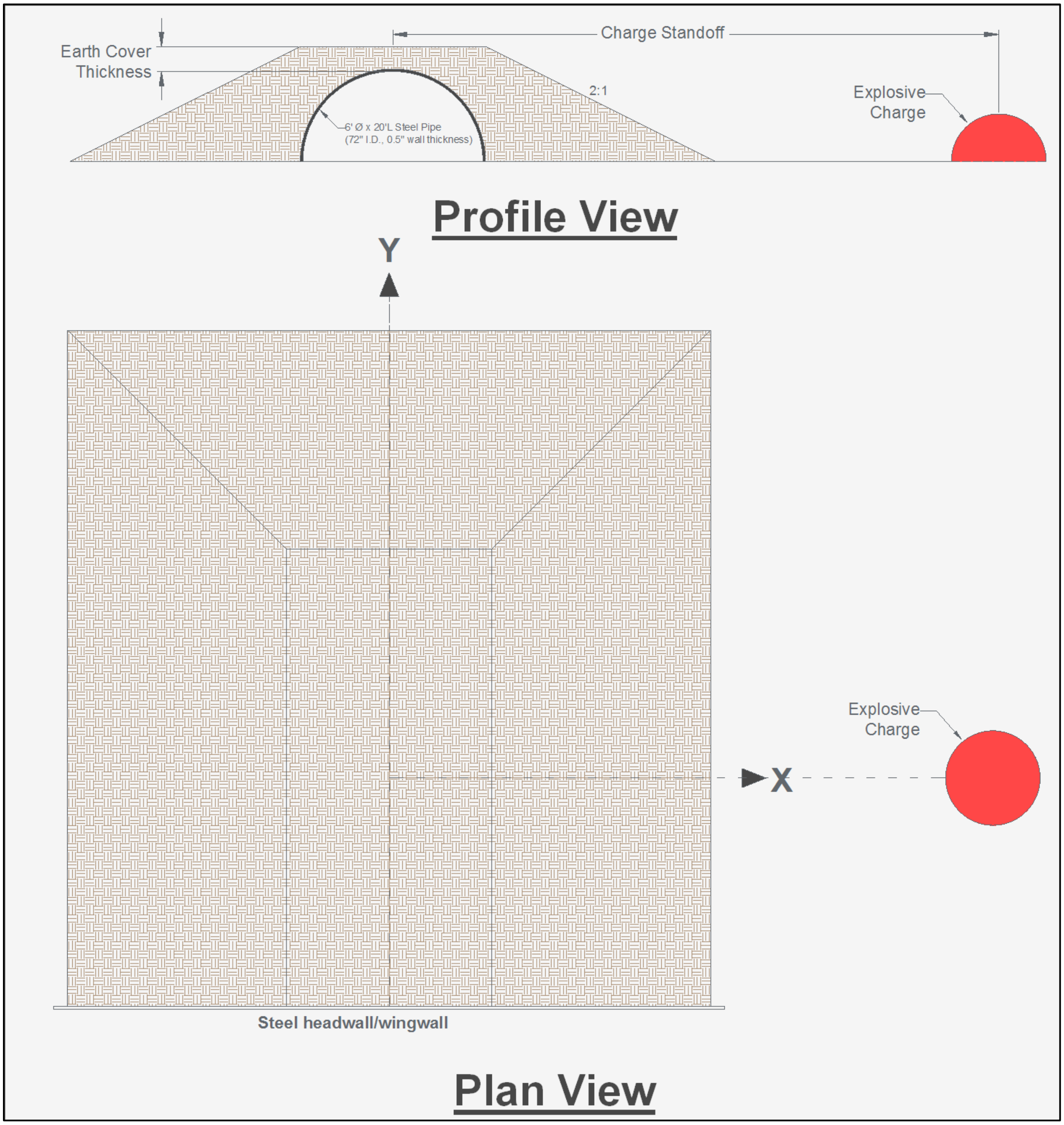

Figure 2. Profile and plan views of testbed configuration.

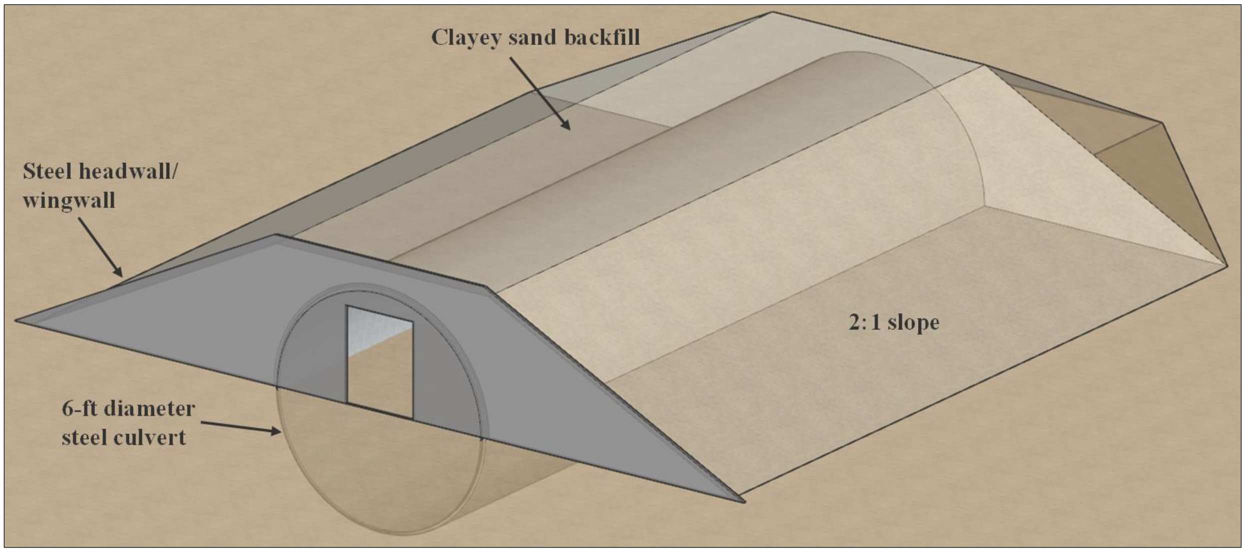

Figure 3. The ECM berm model.

Instrumentation / Data Collection

Ground surface overpressure gauges will be fielded as shown in Figure 4 to capture overpressure along the acceptors position and in the free field. Individual gauge locations for each experiment are shown in Tables 2 and 3. Interface stress measurements will be fielded to capture soil loads transmitted directly to the acceptor's surface, as shown in Figure 5. Individual gauge locations for each experiment are shown in Table 4. Real-time and high-speed video will be captured for each experiment, along with aerial imagery and still photography. Pre- and post-test 3D LiDAR scans will be captured to document test configurations for each experiment.

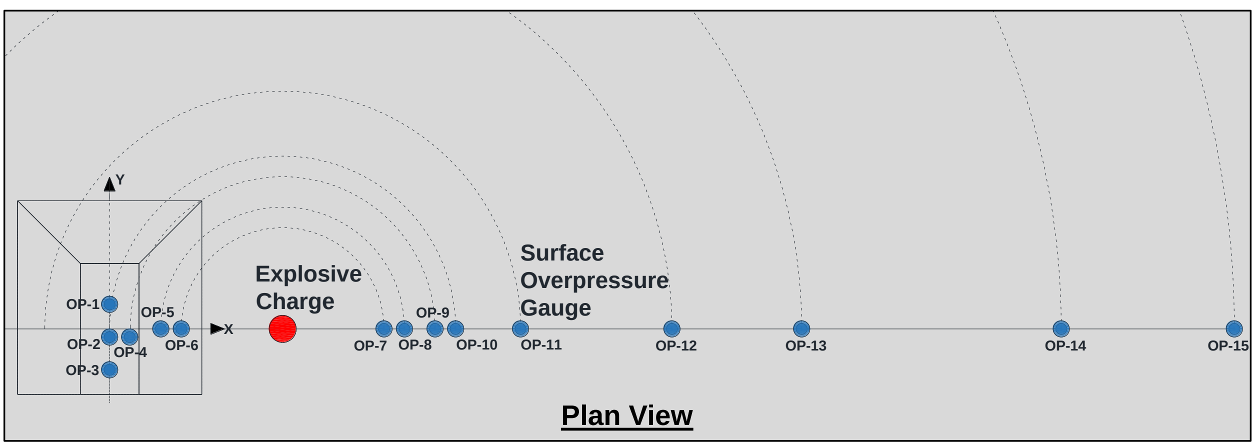

Figure 4. Plan view of overpressure gauge layout for each experiment.

Table 2. Overpressure gauge locations for MERCURY 1.

Gauge Number	X Distance (ft)	Y Distance (ft)	Distance from Charge (ft)	Scaled Distance ($ft/lb^{1/3}$)	Gauge Number	X Distance (ft)	Y Distance (ft)	Distance from Charge (ft)	Scaled Distance ($ft/lb^{1/3}$)
OP-1	0.00	3.00	38.90	3.68	OP-9	71.31	0.00	32.53	3.08
OP-2	0.00	-1.00	38.79	3.67	OP-10	75.11	0.00	36.33	3.44
OP-3	0.00	-5.00	39.10	3.70	OP-11	77.56	0.00	38.78	3.67
OP-4	2.45	-1.00	36.34	3.44	OP-12	86.33	0.00	47.55	4.50
OP-5	6.25	0.00	32.53	3.08	OP-13	102.18	0.00	63.40	6.00
OP-6	8.75	0.00	30.03	2.84	OP-14	133.88	0.00	95.10	9.00
OP-7	59.91	0.00	21.13	2.00	OP-15	155.02	0.00	116.24	11.00
OP-8	68.81	0.00	30.03	2.84					

Table 3. Overpressure gauge locations for MERCURY 2 and 3.

Gauge Number	X Distance (ft)	Y Distance (ft)	Distance from Charge, ft	Scaled Distance ($ft/lb^{1/3}$)	Gauge Number	X Distance (ft)	Y Distance (ft)	Distance from Charge, ft	Scaled Distance ($ft/lb^{1/3}$)
OP-1	0.00	3.00	TBD	TBD	OP-9	TBD	0.00	TBD	TBD
OP-2	0.00	-1.00	TBD	TBD	OP-10	TBD	0.00	TBD	TBD
OP-3	0.00	-5.00	TBD	TBD	OP-11	TBD	0.00	TBD	TBD
OP-4	2.45	-1.00	TBD	TBD	OP-12	TBD	0.00	TBD	TBD
OP-5	6.25	0.00	TBD	TBD	OP-13	TBD	0.00	TBD	TBD
OP-6	8.75	0.00	TBD	TBD	OP-14	TBD	0.00	TBD	TBD
OP-7	TBD	0.00	TBD	TBD	OP-15	TBD	0.00	TBD	TBD
OP-8	TBD	0.00	TBD	TBD					

Table 4. Interface stress gauge locations for MERCURY 1, 2, and 3.

Gauge Number	X Distance (ft)	Y Distance (ft)	Angle (deg)
IF-1	0.00	5.00	90
IF-2	0.00	1.00	90
IF-3	0.00	-3.00	90
IF-4	1.79	-1.00	60
IF-5	3.10	1.00	30

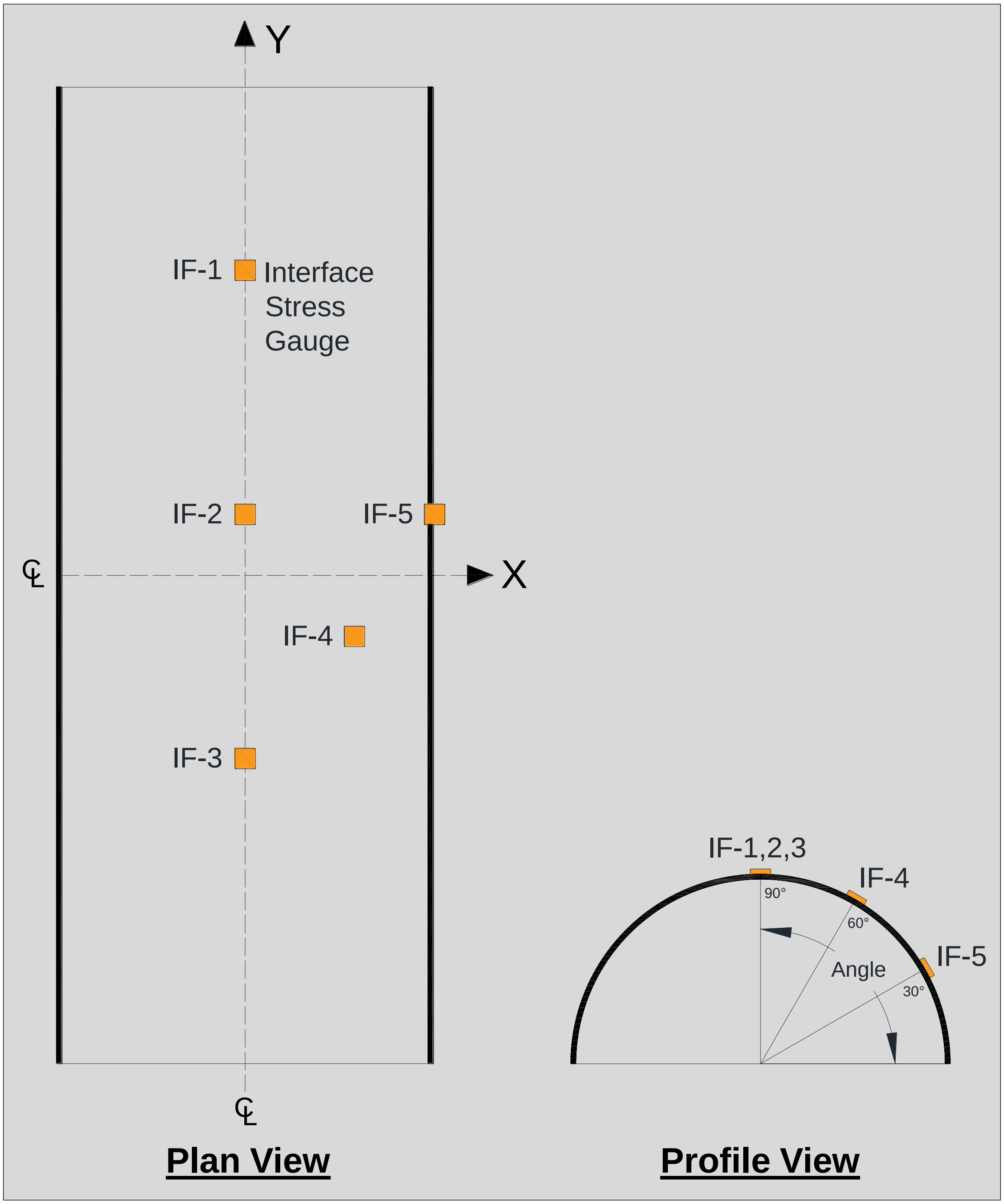

Figure 5. Plan and profile views of the interface stress gauge locations.

Summary and Future Work

A series of experiments (MERCURY Series 1) is planned in FY18 to begin to understand the effects of varying earth-cover thicknesses on acceptor ECM loading. Each experiment will be conducted at ¼ scale of the ESKIMO V experiment. The donor charge will be 922 lb of surface-laid C4 in an approximated hemispherical configuration. Each experiment will feature a half-buried steel culvert to simulate a ¼-scaled arched magazine. Ground surface overpressure and interface stress measurements will be captured to understand the loading on the surface of the soil above the ECM and the loads transferred through the soil to the acceptor ECM. This initial series of experiments will establish a baseline for the loads transmitted to an ECM for a full-scale equivalent earth cover of 2.0 ft (current minimum for designation as an ECM), as well as the transmitted loads at a full-scale equivalent earth cover of 1.0 ft. The results will also help in the planning of experiments proposed for FY19 to further understand the effect of earth cover on acceptor ECM loading due to airblast and fragmentation. In addition, the results will also provide benchmark data for comparison to and validation of results from companion numerical simulations that ERDC has proposed as a means of augmenting the evaluation of the effect of ECM earth cover. If funded, the numerical effort will utilize the existing test data to verify and validate current modeling and simulation (M&S) technologies used for this effort. If validated, the M&S effort would allow a more detailed analysis of the effect of earth cover on the loads transmitted to an acceptor ECM and the blast effects produced by a donor ECM as a function of earth-cover thickness. The ultimate purpose of this experimental effort is to provide enough data to justify updates to the current ECM cover requirements stated in the *DoD Ammunition and Explosives Safety Standards*.

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