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MASTER

TERRABALLISTIC PROJECTILES SIMPLIFY

REMOTE PRELIMINARY INVESTIGATIONS

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INTRODUCTION

The past two decades have seen the accelerated beneficial development of remote and inaccessible areas, such as mountains, forests, jungles, and the oceans. Projects such as dams, pipelines, tunnels, and transmission lines are routinely planned in such areas, where roads do not exist, and where conventional drilling and sampling equipment are often scarce. In response to this situation, the only remote-sensing technique which has been developed is aerial photography, along with the metric and geologic interpretive methods needed to yield topographic and geologic maps. The methods of multi-spectral photography are expected to extend the uses of aerial photography in the future. It is well understood, however, that remote-sensing is really surface-sensing at the present time; and subsurface intelligence results only from interpretation of the surface information. Clearly, there is a need for subsurface data,

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even if approximate, during preliminary investigations of remote and inaccessible areas.

Since 1962, the Sandia Corporation, in cooperation with Woodward-Clyde & Associates and others, has been developing a *subsurface-sensing* device which can be used for preliminary investigations of remote and inaccessible areas. The technique involves dropping or otherwise propelling a projectile which penetrates the ground. The projectile, which is ballistic throughout its trajectory in the ground, contains instruments to measure the forces felt during penetration, and telemetry equipment to transmit the instrument signals to a ground or airborne receiver. Study of these signals yields approximate subsurface data, as will be described in the body of this paper. Well over 700 full-scale field tests have been conducted as a part of the Sandia/WC&A study. All of the tests were carried out in natural soil and rock materials. Projectiles have successfully penetrated natural deposits of loose to dense moist sands, dense cemented sands and gravels, soft estuarine muds, stiff moist to saturated clays, hard dry silty clays, loessial permafrost, glacial ice, dense gypsite, and salt water; projectiles have also penetrated significantly into intact bedrock such as dense sandstone, granite, welded tuff, and dacite. Projectiles from 1 to 18 inches in diameter have been used. Penetrations approaching 100 feet in depth have been successfully accomplished; and depths of 200 to 300 feet in soil are possible, should there be a requirement. The determination is usually done entirely from the

air, and the resulting data identify the soil profile, weak and strong soils, granular and cohesive soils, and layer interfaces including bedrock. The profile data are similar to those from a Standard Penetration Test, and can be used with about the same degree of confidence. Obviously such data would not be adequate for final design; but they are quite useful for preliminary or feasibility studies, especially if alternate sites are being compared.

Interestingly, the performance of terraballistic projectiles has enjoyed a great deal of study over the last two centuries. In fact, one of the best known analytical approaches to the problem was developed by Poncelet, a name well known in soil mechanics. A good review of the work prior to World War II has been given by Robertson (Ref.1). All early work seems to have been done for specific, and military, applications such as the penetration of earth revetments by cannon balls. Pope (Ref. 2) has presented some particularly spectacular results which a German artillery group achieved while developing penetrating rounds for use against Maginot-Line type of fortifications. One round, for example, penetrated a trajectory consisting of 50 feet of "loose stone and clay" overburden, 60 feet of "chalky marl" rock, and 2.5 feet of 10,000-psi heavily reinforced concrete before exploding in a bunker buried 113 feet below the ground surface.

Such results, later verified by the Sandia/WC&A study of instrumented projectiles, have led to two useful conclusions: (1) the penetration of most soils and rocks in a stable trajectory

is really not too difficult if the projectile is properly designed; and (2) the penetration environment, expressed as deceleration (force) is quite mild, usually a few hundred g's in soils and a few thousand g's in rocks. A third, and critically significant, conclusion has resulted from the instrumented experiments over the last 6 years: (3) for a given projectile impacting at a given velocity, the decelerations and penetrated depth depend on the properties of the soil and rock media being penetrated. Thus, if the impact velocity and properties of the earth medium are known, the decelerations and final depth of a given projectile can be predicted; and, more importantly, if the decelerations and depth are known for a particular projectile and impact velocity, it is possible to determine the properties of the earth media being penetrated.

In this paper, the projectile and its application will be described briefly. More detailed discussions can be found in Caudle, et. al. (Ref. 3), Caudle, et. al. (Ref. 4), Woodward-Clyde & Associates (Ref. 5), Young (Ref. 6), and in the lists of references contained in those documents.

MECHANICS OF TERRABALLISTIC PROJECTILES

A terraballistic projectile is a particularly simple device, as shown in Figure 1. The projectile, usually made of mild steel, is long and slender, and has a pointed nose. The *afterbody* is hollow so that the *center of gravity* will be forward for aerodynamic and terradynamic stability, and to house the required *instrument package*. The *fins* are provided for stability in the aero and terra flight modes.

The instrument package contains the accelerometers, to measure the force felt by the projectile; and the amplifying and transmitting equipment required to condition and transmit the accelerometer signals. Transmission is accomplished through a long antenna which trails behind the projectile during its excursion. The antenna is usually folded into the hollow afterbody before test, and is deployed by a small parachute at the proper time. The instrument package, which must ^{withstand} substantial shock during the penetration event, is shock-isolated. } W/O

When allowed to impact the ground surface at high velocity, the projectile penetrates and transmits its decelerations as a function of time. The required velocity can be generated in several ways, but the simplest is to drop or throw the projectile, at a suitable height, from an airplane or helicopter. Figure 2 shows a large projectile being lifted to suitable height by a commercial light helicopter, for release using the helicopter's cable and hook.

When the projectile hits the ground, the sharp nose slices into the soil, as shown in Figure 3(a). At *high velocities*, the slicing action of the nose imparts considerable lateral velocity to the soil particles, pitching them laterally away from the body as it passes by, as shown in Figure 3(b). Thus, almost no side friction exists along the projectile body: projectiles which are recovered almost always have their body point intact, although their noses ^{MAY BE} ~~are~~ considerably eroded and deformed. ^{DEPENDING ON THE MATERIAL PENETRATED} At lower velocities, the laterally pitched soil rebounds before the projectile passes, gripping the projectile tightly and with tremendous force to stop it almost immediately, as shown in Figure 3(c). The fins are designed so that the larger aerodynamic fins shear off at the ground surface, Figure 3(b), leaving the smaller terradynamic to help stabilize the underground trajectory. The resulting trajectory hole is always smaller than the projectile, Figure 3(c), and remains open except in the softest of soils.

As it penetrates, the projectile transmits the decelerations it is experiencing. The results, for a *single-soil uniform profile*, are typically like those in Figure 3(d), and will now be described. At early times, the decelerations rise rapidly to large (not necessarily maximum) values as the projectile enters at high velocity (point W). Often, small-impulse spikes are seen on the record as the fins shear, or as the trailing line stabilizes in the hole. As the penetration proceeds, the velocity and the

resulting decelerations decrease, yielding a plateau (region X in the figure), which is sensibly smooth for a *uniform profile*. Near the end of the penetration, when the soil starts to grip the projectile, the decelerations rapidly increase and the velocity sharply drops to zero, yielding a large (and often maximum) terminal-deceleration peak (point Y). Heavy projectiles thus gripped often evidence a cycle or two of terminal oscillation (point Z), which apparently is essentially elastic.

The raw deceleration-time data are easily (and reliably to a few percent) integrated to obtain depth. The results are then plotted in their proper form for analysis, which is a *deceleration-depth curve*, as shown in Figure 3(e). All of the essential elements of the data appear on the deceleration-depth curve (W, X, Y, and spikes); but the *plateau*, X, is the most important part because it depends strongly on soil or rock properties for a given impact velocity. By study of the deceleration plateau (or plateaux, for multi-layered profiles), it is possible to deduce soil properties and soil types within the penetrated profile.

DISCUSSION OF TERRABALLISTIC DATA

The data from a *uniform* profile have been discussed above, and presented in Figure 3(e). Such data are seldom developed, however, because uniform profiles exist only rarely in nature: a deposit of sand of uniform density would not be uniform in strength because of the effect of overburden confinement; and a deposit of clay would not likely be uniform either in density or strength because of the consolidating effect of overburden.

For example, Figure 4 shows the result of a terraballistic penetration into the well known San Francisco Bay Mud. That deposit, although slightly underconsolidated, increases in strength with depth. At the location of the investigation reported on Figure 4, the soil profile (verified by later conventional drilling and sampling) consists of a top layer of desiccated Bay Mud, overlying the main 70-foot layer of Bay Mud. The underlying materials are stronger sands, clays, and silts in layers as shown. The high initial peak of 16 g's, point 1 on the figure, is composed of the usual initial-impact deceleration and the deceleration due to the (harder) desiccated layer. From these deceleration data alone, it would not be possible to deduce the existence of the desiccated layer; but if the deposit were known to be estuarine, if the deeper data showed the material to be a soft clay (as it does), and if the surface of the deposit were exposed to view (as in this case), then the presence of a desiccated layer would be suspected. In that

case, the depth of the maximum high initial peak yields an estimate of the thickness of the desiccated layer, here about 3 feet. After the projectile penetrates into the main Bay Mud layer, the decelerations drop to the extremely low value of about 10 g's. The decelerations then *increase* with depth [rather than to *decrease*, c.f. Figure 3(e)] in response to the increasing strength of the Mud. In this case, because the hole closed after the projectile passed, the trailing line apparently entangled and was gripped by the soil, as shown by the spikes, points 2, 3, and 4. These spikes could also represent thin layers of dense sand, but the likelihood is small. The bottom of the Bay Mud layer is clearly evident at about 72 feet, where the decelerations rapidly increase to about 90 g's. Although the lower layers are too thin to develop a clearly diagnostic plateau, the abrupt changes in deceleration do show the interface locations to about the same degree of accuracy which would result from conventional drilling and sampling, and to the accuracy which would be required for feasibility studies. It is interesting to note that the deepest layer, the stiff clay (blocky), would not have been detected at all because the terminal-deceleration peak occurred at the same depth. Experience has shown that little should be deduced from data in the last few feet because of the terminal-deceleration effect. An exception is, of course, bedrock, which usually spans the deceleration to a maximum level which is appreciably higher than any previous part of the event.

The data in Figure 5 resulted from an investigation of a remote area in Alaska. The locale being studied was flat and thinly wooded, and the investigation was carried out in the dead of winter. The surface was covered by deep snow, and access was extremely difficult. Several terradynamic projectiles had been dropped in the general area before the test shown in Figure 5. Those projectiles had transmitted decelerations in the range of 200 to 400 g's, in interpretable sequences. The results in Figure 5 were unexpected because of the decrease in decelerations to as low as 20 g's at depths from perhaps 4 to 8 feet. When borings were later made, an unfrozen, soft, saturated silt was encountered from 3 1/2 to 8 or 9 feet, with the lower foot or so being semi-frozen transition material over the underlying permafrost, as had been faithfully reproduced and reported by the terradynamic projectile. Subsequent inquiries disclosed that, during the preceding summer, the area around the impact point had been excavated and backfilled. Evidence of the operations was of course obscured by the deep snow at the time of the investigation.

Although data such as those given in Figures 4 and 5 are common, all profiles are by no means so clear-cut. In particular, sands and other naturally variable deposits often yield data which require careful interpretations. Figure 6 is an example of such results for a variable deposit of sand. As the standard penetrations show (right side of figure), the material is loose to about 10 feet,

loose to medium dense to about 30 feet, loose to about 50 feet, and medium dense to the depth of study at about 72 feet. The upper plateau, from about 8 to about 25 or 30 feet, shows a constant or slightly increasing deceleration, indicating that the material is increasing in strength with depth. By detailed velocity-deceleration calculation, one would predict the approximate average of standard penetrations; but one would not predict the apparent sharp change from 2 to 10 blows per foot at about 8 feet. The data do, however, show the apparent sharp change from 23 to 10 blows per foot at about 25 feet. It is important to point out, however, that the drill hole for the standard penetrations was made some 10 feet away from the impact point to avoid "disturbance." One is led to wonder if many experienced soil engineers would be surprised if two similar drill holes 10 feet apart in a natural sand deposit showed the amount of profile variation shown in Figure 6. As a matter of fact, one would interpret the data in Figure 5 as follows: "deposit of loose to medium dense sand, likely loose in the upper 6 to 8 feet, probably loose below 30 feet, but increasing in strength below this depth." For most preliminary studies in natural sand deposits, the experienced soil engineer would not care to be much more specific.

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such applications. Usually the soil-rock interface is expected to show up clearly; but the water-soil interface is sometimes undefined, especially if the boundary material is a flocculated ooze.

THE TERRABALLISTIC INVESTIGATION SYSTEM

The sequence of a preliminary investigation using terraballistic projectiles is given in Figure 8.

A helicopter or light aircraft, equipped with a crude bombsight, is an adequate delivery system. Experience has shown that a gimballed telescope is an adequate sight. Inert practice projectiles containing smoke spotting charges are first dropped to ensure hitting the desired location. After the proper release locations are established, the projectiles are dropped. Experience has shown that determination of the impact point of the projectile, after impact, is extremely difficult from the air or the ground. The use of dye markers or smoke charges carried in the terradynamic projectile has not proved very successful. If the determination of the impact point is important (e. g., for later recovery and re-use of the components), then multiple observation of impact by widely spaced ground observers is required. For these cases, then, a small party of observers is required in the drop area. If only approximate locations are required, then time-distance calculations from the smoke spotting charges are usually adequate.

The only sensing instrument required on the projectile is the accelerometer, but other instruments are sometimes carried for special problems. The receiving and recording facilities can be carried in the drop aircraft or can be placed on the ground if convenient. If desired, a high-power transmitter can be carried on the aircraft for immediate transmittal of the recorded data to a computer center. In this way, the reduced data can be available for analysis shortly after the drops are made.

Figure 8 shows the sequence of events in a site profile investigation using earth-penetrating projectiles. The sketch at the top of the figure

shows an assumed actual profile as, for example, might exist at the proposed alignment for a dam in a remote location. An aircraft equipped with the receiving and recording equipment is shown flying the alignment, dropping the projectiles. Five units are shown, each in a different stage of the event: Unit 1 has penetrated to its full depth and has stopped; Unit 2 is still penetrating and is still broadcasting the decelerations it experiences; Unit 3 is shown in free fall, acquiring velocity under the acceleration of gravity; Unit 4 is shown as it starts to stabilize aerodynamically, and as its trailing antenna starts to deploy; and Unit 5 is shown just as it is released from the aircraft.

For the profile shown, the deceleration-depth records would be as given in the middle sketch of Figure 8. Unit 1 would experience severe and highly varying decelerations as it penetrated the dense gravel and talus deposit. That material, noted on the lower sketch of Figure 7 as material A, would be identified as dense because of the high value of the decelerations; and as either large grained or highly erratic because of the large variations in deceleration. Upon entering the medium dense sand, Unit 1 would experience moderately high decelerations, and the record would show the mild variations, similar to electronic noise, but at a much lower frequency, which are diagnostic of sandy deposits. That material, noted as material B on the figure, would be identified as medium dense to dense because of the value of the deceleration, as granular, even sandy, because of the mild hackles on the record, and as uniform because there are no pronounced or large variations of deceleration. Upon entering the underlying bedrock, Unit 1 would experience a pronounced increase in deceleration, as shown in the figure, with the very high terminal value as the projectile is seized by the medium. That material, noted

as material F on the figure, might be identified as a rock of moderate to weak strength. However, from the relative values of deceleration on the deceleration depth curve shown in Figure 8, it would be difficult to ascertain from this single record whether the material was a very competent soil or a moderate to weak rock. This same uncertainty often exists in conventional investigations of sedimentary rocks underlying competent soils. By comparison to the other records, however, one could observe the apparent uniformity of the decelerations; and, if the general geology of the area indicated the probability of such sedimentary rocks, the preliminary bedrock conclusion would be justified. If the presence of rock were a critical factor in the study, then a second run at higher velocities (higher drop altitude) would be done in order to penetrate further into the suspected rock material.

Unit 2 (Figure 8) would experience moderately high decelerations with minor variations on the record in the upper medium dense sand; and by comparison to the nearby Unit 1 results, that material would be identified as B. When Unit 2 passed through the soft clay, the deceleration level would drop appreciably before the terminal very high deceleration upon contact with the rock, where the unit is stopped with little penetration. The identification of materials B and C would follow from comparison to the records of the other units. The identification of the bottom material as F would, however, be somewhat uncertain: the high terminal deceleration as shown could just as well have occurred if some more material B underlay material C. The data for Unit 4 in Figure 8 shows this case, with the uncertainty indicated. Such uncertainties will exist for the general case of a moderately strong soil overlying a moderately weak rock. In this case, the projectiles should be impacted with enough velocity to carry them well into the rock. If the underlying rock

is strong, then identification of the rock surface is much more certain. In fact, if weak soils overlie any rock, or if strong rock underlies any soil, then the projectile technique is a very reliable method of determining the depth of the bedrock surface.

COSTS

Because terraballistic investigations do not yet enjoy widespread use, the costs must be expected to vary greatly from project to project at the present time. The costs will depend strongly on the number of projectiles (investigation points) required. Projectiles can be recovered, by excavation, and re-used. The costs of recovery of deeply penetrated projectiles in remote areas must be calculated to determine if recovery is economical. If recovery appears economical, then it may ultimately be more economical to use conventional methods because the recovery of the conventional equipment will be about the same.

The highest unit cost is the instrument package. Depending on the deceleration environment, the final depth expected, and the number of projectiles required, the costs of the instrument packages vary from perhaps \$2,000 to \$4,000 per projectile. This could be 2 to 3 times the cost of maintaining a drill rig and crew in the field for the 2 to 3 days required to drill an equivalent 100 foot hole.

In order to field a rig and crew to a remote area, substantial mobilization and demobilization expenses must be expected. The equivalent expenses using terraballistic projectiles are the costs for airplane, receiver rental, computer time, and personnel costs. The airplane costs vary with locale and area, and will not be discussed here. The costs for receiver rental range from \$2,000 to \$10,000, depending on the type of equipment required and the duration of the study. Computer costs are usually small if a big machine is used. Personnel costs should be expected to be \$300 to \$500 per day.

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From these approximate cost figures, it is clear that the method is economical only if normal access is a substantial expense, or if experienced rigs and crews are not available. The costs mentioned here are expected to decrease substantially in the future for large projects or for repeated applications, particularly if projectiles are recovered later during construction operations.

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SUMMARY

The work described and the data collected have shown that soil investigations using terraballistic projectiles can be useful, provided:

1. Approximate data, about equivalent to the standard penetrations, are adequate for the project;
2. The area is remote and inaccessible, so that conventional investigations are expensive or impractical;
3. If time is important, and the project cannot wait for the slow methods of conventional investigations.

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FIG. 1. Details of Terraballistic Projectile

FIG. 2. Helicopter with Terradynamic Projectile.
-shown commencing climb to suitable
height

(a) INITIAL IMPACT

(b) DURING PENETRATION

(c) AT REST

(d) RAW DATA
PLOTTED AGAINST TIME

(e) DATA IN USEFUL FORM
PLOTTED AGAINST DEPTH

FIG. 3. The Earth-Penetration Event
(sketches, no scale)

FIG. 4 Example of Terraballistic Penetration in Soft, Saturated Soils Which Increase in Strength With Depth.

FIG. 5 Example of Terraballistic Detection of a Soft Zone (here, in Permafrost)

FIG. 6 Example of Terradynamic Penetration in Natural Variable-Density Deposit of Moist Sand

FIG. 7 Example of Data From Terraballistic Projectile
Dropped Offshore

Note: Scale of record distorted for clarity.

FIG. 8. Preliminary Soil Investigation Using Terraballistic Projectiles