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MATERIALS FOR USE IN MITIGATING BLAST LOADS ON DEEPLY BURIED PROTECTIVE STRUCTURES

by

G. C. Hoff

March 1966

U. S. Army Engineer Waterways Experiment Station
CORPS OF ENGINEERS
Vicksburg, Mississippi

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Foreword

This paper was prepared for presentation at the 1966 Army Science Conference at West Point, New York. It was approved for presentation and publication by the Office, Chief of Engineers. The paper was prepared by Mr. George C. Hoff, under the general supervision of Mr. James M. Polatty, Chief, Engineering Mechanics Branch, and Mr. Bryant Mather, Acting Chief, Concrete Division, U. S. Army Engineer Waterways Experiment Station.

Director of the Waterways Experiment Station during the preparation of this paper was Col. John R. Oswalt, Jr., CE. Technical Director was Mr. J. B. Tiffany.

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TITLE: Materials for Use in Mitigating Blast Loads on Deeply Buried Protective Structures.

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ABSTRACT:

The structural design of deeply buried protective structures to resist the effects of nuclear blast loading is somewhat simplified if the structure can be designed to resist a defined, constant or quasi-constant stress level when shock-loaded. By backpacking a buried structure with certain types of materials, a constant stress level can be obtained when a shock wave is transmitted through the backpacking to the structure. These backpacking materials also act to (a) dissipate a portion of the shock energy, (b) reflect a portion of the shock energy, and (c) absorb flyrock from the containing medium. A program to investigate and develop materials of this nature was initiated at the Waterways Experiment Station and was sponsored by the Defense Atomic Support Agency.

An analysis of the desired behavior of the material accompanied by existing theories and postulates pertaining to the use of backpacking materials resulted in the defining of a variety of materials that could conceivably be used as backpacking materials. Materials that were considered included lightweight concretes, foamed plastics, honeycombs, and natural aggregates. These materials were evaluated as to their physical properties and behavior, availability, and emplacement procedures and costs. Based on the results of these evaluations, three of the materials investigated are currently being utilized in an actual nuclear blast field test using prototype structures.

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MATERIALS FOR USE IN MITIGATING BLAST LOADS ON DEEPLY BURIED PROTECTIVE STRUCTURES

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The field of structure-medium interaction has long commanded the attention of individuals concerned with the design and construction of buried structures. With advances in the use of thermonuclear weapons, the difficulty in understanding structure-medium interactions and therefore the designing of buried structures have become further complicated by the introduction of complex ground motions and very high applied loads. The design of buried structures to resist these effects usually results in design loads which are so high that overconservative design would be extremely costly. On the other hand, catastrophic failure of the structure due to an inadequate design cannot be tolerated.

The applied forces for which a blast-resistant structure must be designed are transient in nature, and their probability of occurrence is small. The magnitude of these forces depends on a number of factors over which a designer has no control. To eliminate some of the many unknowns imposed on the structural design of a buried structure, the designer may employ various structural systems in selected environments which will increase the probability of survival of the structure and its contents. It is the purpose of this paper to describe a technique that can be used for controlling the magnitude of the forces being applied to buried structures by blast loading, i.e. the use of backpacking materials for shock isolation of buried structures.

BACKGROUND

Interest in the use of backpacking for shock isolation of entire buried structures has generated many ideas as to the feasibility and composition of various systems and materials that could be satisfactorily used as backpacking. As early as 1953, Engineering Research Associates, et al. (6), in a report to the U. S. Army Corps of Engineers on underground explosion test programs, suggested that: "The space between the lining and the tunnel surface should be filled with a material of low density that will absorb the energy of the

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flying rock, distribute the pressure from the fallen rock, and provide a mismatch of acoustic impedance so that reflection will take place at the tunnel surface rather than at the surface of the lining."

In 1957, Vaile (24) reported on the beneficial use of a frangible backfill in isolating and protecting underground structures in Operation PLUMBBOB from violent ground motions in their vicinity. During Operation PLUMBBOB, vertical concrete pipes covered with concrete slabs were lined one layer thick on the sides and bottom with empty, glass, quart gin bottles. When compared with the control pipe for the experiment, which had soil backfilled directly against it, it was found that the peak accelerations produced by shear forces exerted on the sides of the isolated pipes were reduced to 26 percent of those experienced by the control pipe. This reduction was attributed in part to the collapse and crushing of the glass which dissipated a portion of the shock energy.

In two related studies by Sevin, et al. (18,19), at the Armour Research Foundation (now the Illinois Institute of Technology Research Institute), various devices were employed on or about cylinders buried in silica sand in order to alleviate shock-induced motions of the cylinders. These devices consisted of (a) wrapping of the cylinders in flexible and rigid polyurethane foams, (b) the use of air voids between the medium and cylinders, (c) use of preexpanded polystyrene beads as a crushable backfill aggregate, and (d) the use of sand of varying densities as backfill aggregate separated from the overall bed by a stovepipe. The conclusions reached were that the polyester urethane foams placed around a cylinder and other materials functioning as a loose backfill aggregate were effective in attenuating the response of the isolated structures.

Da Deppo and Werner (3), in a study on the influence of mechanical shielding on the response of buried cylinders, introduced a crushable layer directly over the buried cylinder. The use of this crushable material greatly reduced the magnitudes of the loads reaching the cylinder.

Fowles and Curran (7), in presenting theoretical descriptions of the propagation of a pressure pulse in a potential backpacking material, suggest that foamed or distended materials are effective in reducing the peak pressures delivered to a structure when an impulse is applied to the opposite surface of the foam.

In discussing the methods of mitigating the effects of shock for lined tunnels in rock, Newmark and Merritt (16) state that the current design concept for protective linings in competent rock includes the provision for a highly deformable material between the face of the rock and the lining: "It would appear that the magnitude of ... forces (generated by small impacts) reaching the lining could be significantly reduced if a crushable material is introduced between the face of the rock and the lining."

Smith and Thompson (21) suggest that the shock energy reaching a buried structure in rock can be partially dissipated by (a) reflection of energy, and (b) energy absorption. They suggest that these requirements be met by interposing a material between the structure and the confining medium that has a low shock impedance with

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respect to that of the confining medium. The impedance mismatch which occurs will cause some energy to be reflected. If the low-shock-impedance material is also very deformable under applied loads, it will absorb the energy present in the form of ground motions, thereby meeting the two requirements.

DESIGN CRITERIA

A review of the investigations cited above and other similar projects provides an insight as to what is necessary in designing a backpacking system for shock-isolation purposes. In general, a suitable backpacking should be a frangible or crushable material possessing a low breaking or crushing stress level and a high degree of compressibility. If possessing these characteristics, the material should dissipate a portion of the shock energy, thereby reducing the magnitudes of the forces reaching the structure and should accommodate the deformations of the cavity in which the structure has been placed. Due to the large relative costs of construction versus design overpressures, the scope of interest of this paper will be limited to design overpressures less than 1000 psi; i.e. the magnitude of the stress transmitted to the structure through the backpacking will be less than 1000 psi. Assuming single-burst loading where closure of the cavity is imminent, deformations of the backfill to accommodate this closure should be approximately 50 percent. In other cases it may be considerably less.

THEORY

Pressure-Volume, Stress-Strain Relations

The majority of the materials investigated both in the past and at present generally fall into two distinct categories: (a) materials having no distinct yield point and some degree of compressibility, and (b) materials possessing a distinct yield point and some degree of compressibility. Ideally these materials can be represented by pressure-volume curves for a simple-rigid locking solid (Figure 1) and an elastic-rigid locking solid (Figure 2), respectively (7).

Consider first the case of a simple-rigid locking solid (Figure 1). The original volume is designated V_o . Under a very small applied pressure, the specific volume decreases to V_1 at no appreciable increase in the pressure. At V_1 , the material locks with no further decrease in volume occurring with additional increases in the pressure.

In the case of the elastic-rigid locking solid (Figure 2), the pressure-volume curve is very similar to that of the simple-rigid locking solid but with the addition of an elastic region containing a definite yield point. As in the previous case, the initial specific volume is represented by V_o . Under application of pressure the material behaves as an isotropic elastic solid until P_e , the elastic yield pressure, is reached. Beyond that pressure, the material behaves like a simple-rigid locking solid.

Under blast loading conditions, the loaded area is normally

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so great that the portion of the medium under consideration and its inclusions can be assumed to be laterally confined with displacements occurring only in the direction of loading. By applying this assumption of lateral restraint to the ideal pressure-volume curves, they can readily be converted to stress-strain curves for simple-rigid and elastic-rigid locking solids subjected to one-dimensional compression (Figure 3). To indicate more clearly the behavior of real materials, the locking portion of the curves has been shown as an inclined line representing the elastic behavior of the solids composing the materials under consideration. With the addition of this elastic portion, the simple-rigid and elastic-rigid locking solids will hereinafter be referred to as plasto-elastic and elasto-plastic materials, respectively. This conversion to a stress-strain relation provides a convenient tool for evaluating the energy-dissipating capability of the materials.

Energy Absorption

The energy absorbed by a material depends on two factors: (a) the deformation of the material, and (b) the forces in the material during the deformation (5). The product of the strain and the unit force results in the amount of energy absorbed by the materials:

$$E_n = \bar{\sigma} \times \epsilon = \text{area under the stress-strain curve (Figure 4)} \quad (1)$$

E_n is expressed as the energy per unit volume of material and can be shown for all cases to be

$$E_n = \int^{\epsilon} \sigma \cdot d\epsilon \quad (2)$$

From the energy relations just described, it becomes obvious from the shape of the stress-strain curves that elasto-plastic materials are more efficient energy absorbers than plasto-elastic materials. Both materials are under consideration for use as backpacking, however, because the plasto-elastic materials may be more economical and thus more attractive when large volumes are necessary.

Stress Transfer

When the closure of the cavity containing a backpacked liner is uniform, the deformation of the backpacking will also be uniform, and hence, if the backpacking is homogeneous and isotropic, the circumferential stress transferred to the structure will also be uniform. The magnitude of the stress reaching the structure will depend on the load-deformation characteristics of the backpacking plus the amount of deformation occurring. If, however, the deformation or stress in the backpacking is nonuniform, the liner will tend to deform into an oval or elliptical shape as shown in Figure 5.

Newmark (15), in discussing the factors to be considered in designing blast-resistant and ground-shock-resistant structures, approached this problem by letting the lining deform by such an amount so as to develop in the backpacking appropriate resisting stresses

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against the deformation. The lining must, in this case, have requisite strength in compression and buckling, and must be able to deform sufficiently, without failure or fracture, in order to develop the required resistance.

In developing the stress-transfer theory, Newmark (15) allowed a and b (Figure 5) to represent the displacements of the cavity walls. However, because of the deformations, y , of the liner itself, the net change in thickness of the backpacking at the sides is b - y and a + y . By assuming a general situation of load-deformation for an elasto-plastic material (Figure 6), it can be readily seen that the magnitude of the net differential pressure between points b and a , assuming the lining does not deform, is much greater than the net differential pressure between points b - y and a + y . If b - y and a + y are expressed as $q + p_1$ and $q - p_1$, respectively, it can then be said that the average of these pressures is the uniform component of load, q , and that the difference from the average is p_1 , the inward or outward component of load. It is this component of load, p_1 , which tends to produce the elliptical or oval deformation of the lining. As can be seen from the ideal curve in Figure 6, the larger the net differential pressure, the greater p_1 is. When p_1 is large, the deformations of the lining are large. When lining deformations are large, the backpacking is compressed more, thus causing the pressure differential to become smaller, which in turn reduces p_1 and thus the deformations of the lining and so on until an equilibrium is reached at a uniform pressure, q . If the deformations of the cavity are such that point b lies on the yield plateau of the load-compression curve for the backpacking, the maximum stress transferred to the structure will be equal to or less than the yield strength of the backpacking.

This same approach to stress transfer can be implemented using a load-deformation relation for plasto-elastic materials but with a little more difficulty as it is relatively impossible for a lining interacting with the progressively increasing stress-strain relation of a plasto-elastic material to develop a resistance characterized by a nearly uniform compression on all sides.

Thickness Determinations

In general, the backpacking is most effective when designed to have an energy-absorbing capacity equal to that of the core of material removed to form the cavity (15). For a plane wave of stress, assuming average deformations of the cavity, the total strain energy, both elastic and plastic, which would have existed in the core of material that was removed can be evaluated and equated to the relation shown in Equation 2. By trial and error procedures, $\overline{\sigma}$, the average plastic stress in the backpacking, and, ϵ , the plastic strain in the backpacking, can be evaluated (11). The total plastic strain plus volume allowances for the solid elastic particles of the backpacking form the basis for determining the thickness, t_r of the backpacking. When the cavity is in rock, the bulking phenomena and the kinetic energy of spall projectiles must also be considered in the thickness determination (15).

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MATERIALS

The two ideal stress-strain relations shown in Figure 3 define the properties of a variety of materials. Figure 7 shows the relation between the ideal and typical stress-strain curves for both types of materials.

The typical curve shown in Figure 7a represents the stress-strain relation for materials that do not possess a definite yield point (plasto-elastic) but are still very compressible, either elastically or inelastically, or both. Granular materials are representative materials for this type of curve. Some plastics and rubbers also possess these characteristics. However, the plasto-elastic materials discussed in this paper will be primarily the granular materials.

Figure 7b represents the typical stress-strain curve for elasto-plastic materials compared with the ideal curve. Insulating concretes and plastic foams are good representatives of this class of material, although some granular and other materials also exhibit this type of behavior.

Plasto-Elastic Materials

Granular Materials. Normally the strength of the grains of competent naturally occurring materials is too great to provide the large deformations required before 1000-psi applied pressure is reached. Some naturally occurring grains, however, do possess this deformation capability because of the very friable, vesicular nature of the grain. Klotz (12) reported on one such material, volcanic cinders, in an investigation of various materials for use as backpacking for Operation NOUGAT, Shot HARDHAT. Other naturally occurring materials can be altered by various mechanical and thermal means to produce grains of a composition suitable for shock-isolation purposes. Such materials as expanded clay (10), expanded shale, expanded slag, coke, coal cinders (12), vermiculite (10,21), and perlite (10) have also been investigated by numerous investigators for their shock-dissipating characteristics. Some of the results of these investigations as well as the results of investigations of other materials mentioned in this paper are summarized and depicted graphically in Reference 8.

Artificial grains can also be used for shock-isolation purposes. The waste products of various plastic-foam manufacturing processes often can be adapted for use as a granular material. The industrial waste as well as artificial grains manufactured in the form of chips or aggregate often provides adequate shock-dissipating characteristics. Such artificial materials as phenolic microballoons (7,10), expanded polystyrene beads (10,18), plastic foam chips (10,12), foamed metallic waste, and foamed rubber waste (10) have been evaluated and found adequate. There are many waste materials which could prove adequate, but because waste is not deliberately manufactured, availability and perhaps cost would probably be limiting features.

Foamed Materials. Many foamed materials do not possess a definite yield point but begin to deform with the application of very small pressures. The resulting stress-strain curve is progressively locking and can be assumed to represent a plasto-elastic material.

Elasto-Plastic Materials

Many investigations into the energy-dissipating characteristics of various elasto-plastic materials have been conducted over the years in connection with the packaging industry and the Quartermaster Corps requirements for airdrop cushioning (1,17,22). From these investigations emerged a family of foamed plastics and honeycombs whose stress-strain relations approximate that of the ideal elastic-rigid locking solid. These materials can be fabricated so that the binder will furnish the crushing stress level desired with the fractional volume of voids or pores in the material being controlled so as to obtain the desired deformations. This is not the final answer, however. A good many of the foamed plastics and honeycombs are very expensive and are relatively difficult to handle and place in sufficient quantities and in adverse environments which may be dictated by the design and location of a buried structure. These problems, in general, fostered the need for a relatively inexpensive construction material which would serve the same purpose. Research at the University of Illinois (12), University of Texas (20,21), and the Waterways Experiment Station (10) has shown that insulating concretes, i.e. concretes having an oven-dried density of less than 50 lb/cu ft, while not as efficient as foamed plastics and honeycombs in some respects, will provide the desired shock-isolation characteristics.

Plastic Foams. Not all plastic foams possess an elasto-plastic stress-strain relation. As mentioned previously, the "flexible" plastic foams often produce a plasto-elastic stress-strain relation. "Rigid" plastic foams generally produce the elasto-plastic relation. Both types transfer stress and dissipate energy, but as mentioned before, the elasto-plastic material is more efficient in both respects.

A variety of rigid foamed plastics are available and suitable for shock-isolation purposes, but more often than not, they are extremely expensive. The rigid polyurethane foam is perhaps the most widely investigated (10,20,23) and used (7,14,18) for this purpose. Despite its high cost, rigid polyurethane is still attractive as it is available in most areas, and is fairly homogeneous and isotropic when formulated properly; it possesses the desired stress-strain relation; it possesses the capability of being fabricated in the field and, if closed-cell, is somewhat nonsusceptible to groundwater infiltration which would reduce its energy-dissipating potential.

Other types of foam which have been reported as suitable energy dissipators are polystyrene (10) and polyvinylchloride (7,10). These two materials are also very expensive and are currently available only in relatively small pieces compared with the needs of isolating a structure. The cost of assembling and fitting the small pieces around a structure would be very great.

Honeycombs. The use of prefabricated honeycombs has proved an effective means of energy dissipation and stress transfer. Honeycombs have the advantage of being very isotropic if designed properly

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so that the maximum stress in the packing can always be limited. They can also be largely impervious to groundwater infiltration. The main disadvantage of honeycombs is the large cost that will be incurred in placing the material around a structure.

There are two basic types of honeycombs: paper and metallic. Paper honeycombs are used primarily at stress levels less than 100 psi (5,23), while metallic honeycombs are more effective at stress levels in excess of 100 psi (13). Because of the nature of the composition of the honeycombs, it is doubtful if a good bond between the honeycomb and the structure will be obtained.

Insulating Concretes. Insulating concretes are best defined as concretes made with portland cement, water, air, and possibly aggregate additions to form a hardened material which will have an oven-dried density of 50 lb/cu ft or less.

As in the case of foam plastics, the hardened matrix provides the crushing stress level while the voids necessary for deformation are provided by the air and in part by the aggregate. The strength of the hardened portland cement paste can readily be controlled, but the deformations present some problems. If an aggregate is used, it must be very weak and friable. Regardless of its strength, however, it still contributes somewhat to the overall strength of the hardened mass. Experience has shown that the addition of too much aggregate in order to obtain more deformation adversely affects the workability of the concrete, thus making it very difficult to handle and place. The solution is that most insulating concretes, such as vermiculite (2,10,20,21) and perlite (12) concrete, require as much as 20 to 30 percent entrained air in order to become suitable shock dissipators. Cellular concrete (9,10,12), which may or may not include a fine sand or filler, can often be found with air contents as high as 75 percent of the total concrete volume. All of the insulating concretes are relatively inexpensive when compared with the cost of the foamed plastics and honeycombs and can be fabricated and placed in most environments using conventional construction equipment.

Other Materials. The introduction of a collapsible aggregate into a suitable binder may result in a system possessing an elasto-plastic stress-strain relation. Various types of ultralightweight concretes, plastics with aggregate inclusions, and such foamed binders as epoxy (10), asphalt, gypsum, sulphur (4), and various chemical compounds all possess possibilities as shock dissipators.

SUMMARY

The behavior of a buried structure subjected to blast loading must be evaluated on the basis of the loads reaching the structure. Research has shown that the use of a properly designed backpacking material placed around the structure dissipates a portion of the shock energy present in the free field, thereby reducing the magnitude of the forces reaching the structure. The response of the backpacking then and that of the structure are completely interdependent, and the design of one cannot be considered without the design of the other.

Based on the results of laboratory research (11,13), three

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materials--(a) a naturally occurring friable aggregate, (b) a foamed plastic, and (c) an insulating concrete--are currently being utilized in a prototype experiment to evaluate their shock-dissipating and stress-transfer characteristics. The results of this experiment along with other factors such as cost, availability, and ease of placement will enlighten the future outlook for backpacking materials placed around buried structures.

ACKNOWLEDGMENTS

This paper is based on a research project entitled "Shock Absorbing Concrete" (10), currently being conducted at the U. S. Army Engineer Waterways Experiment Station under the sponsorship of the Defense Atomic Support Agency, Washington, D. C. Appreciation is expressed to all personnel of the U. S. Army Engineer Waterways Experiment Station who assisted in preparing this paper. Col. John R. Oswalt, Jr., CE, was Director and Mr. J. B. Tiffany was Technical Director of the Waterways Experiment Station during the preparation of this paper.

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LIST OF SYMBOLS

a, b = displacements of cavity walls
E_n = energy absorption per unit volume of material
p_1 = varying component of packing pressure on liner
P_e = pressure at elastic yield point of the material
P_o = original pressure
P_1 = pressure at the locking state of the material
q = uniform component of packing pressure on liner
r = radius
t_f = thickness of backpacking
V_e = volume of material at pressure P_e
V_o = original volume
V_1 = volume of the material in the locking state
y = deformation of liner
ϵ = strain
σ = stress
$\bar{\sigma}$ = average stress

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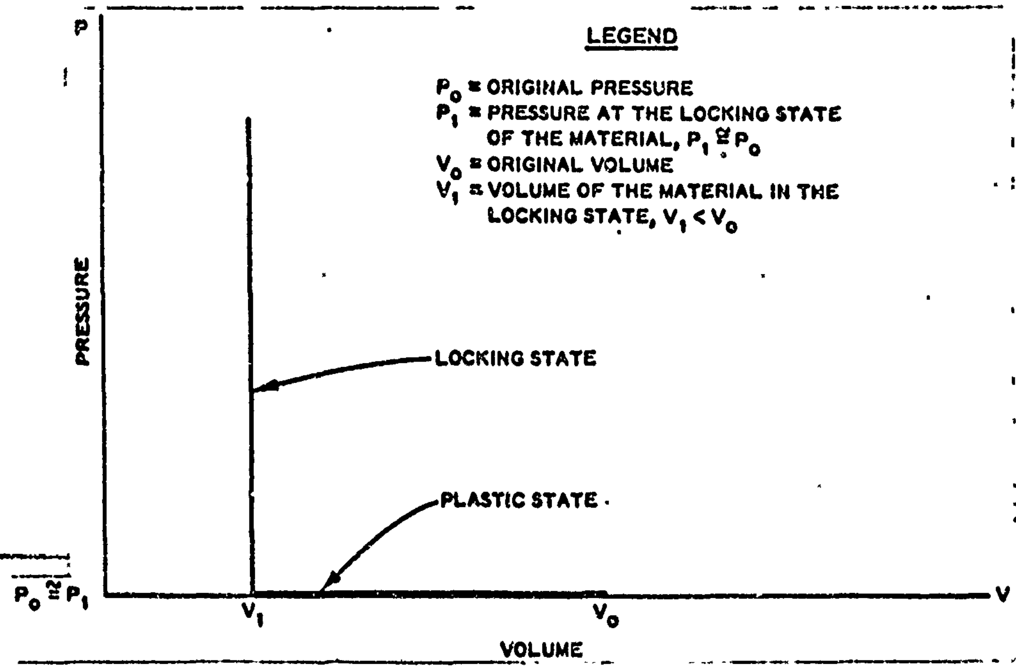

Figure 1. Pressure-volume relation for a simple-rigid locking solid

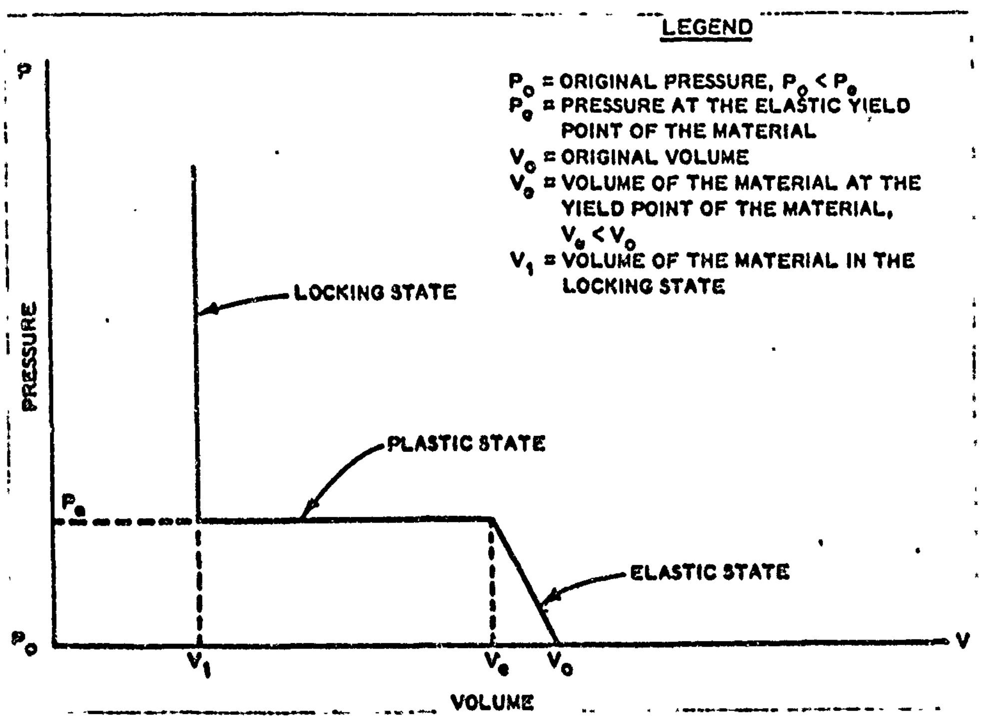

Figure 2. Pressure-volume relation for an elastic-rigid locking solid

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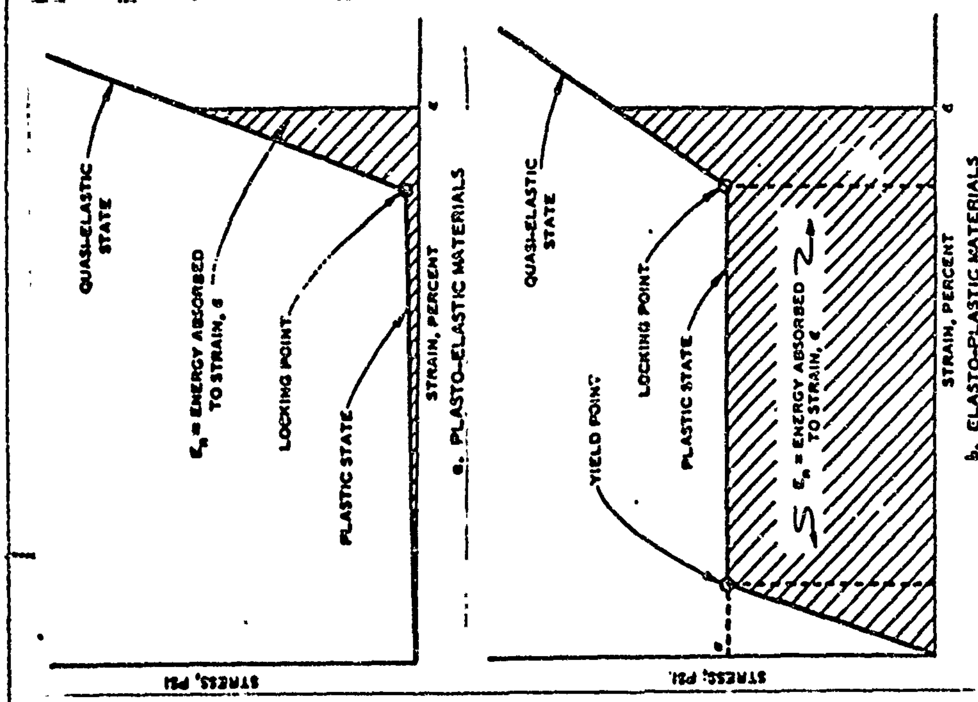

Figure 4. Ideal stress-strain relations showing energy absorbed to a given strain, ε

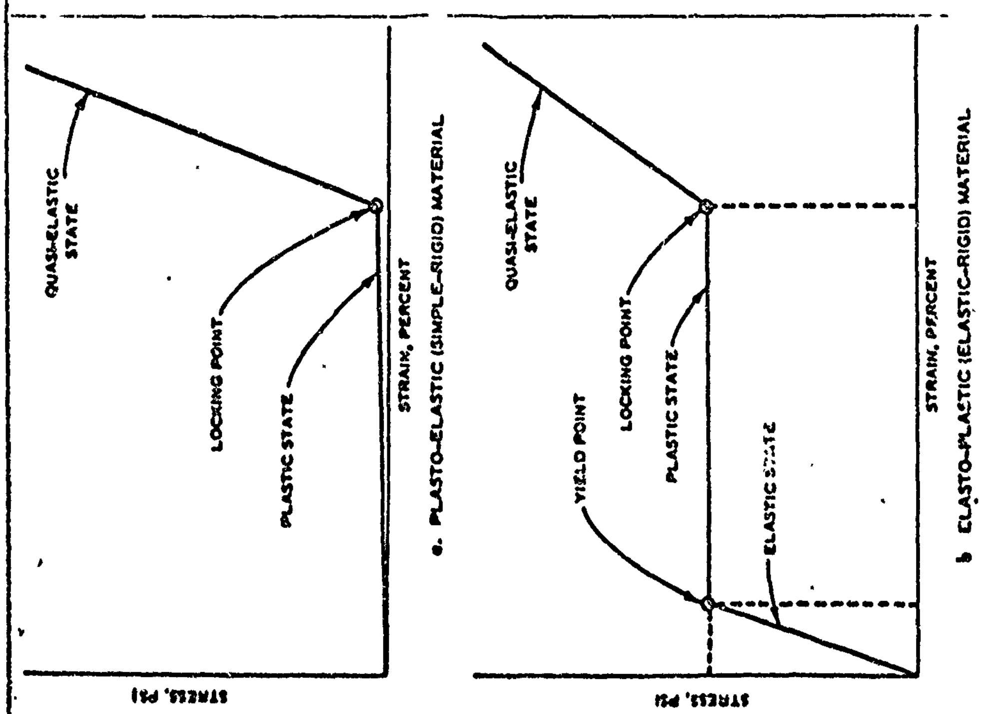

Figure 3. Ideal stress-strain relations

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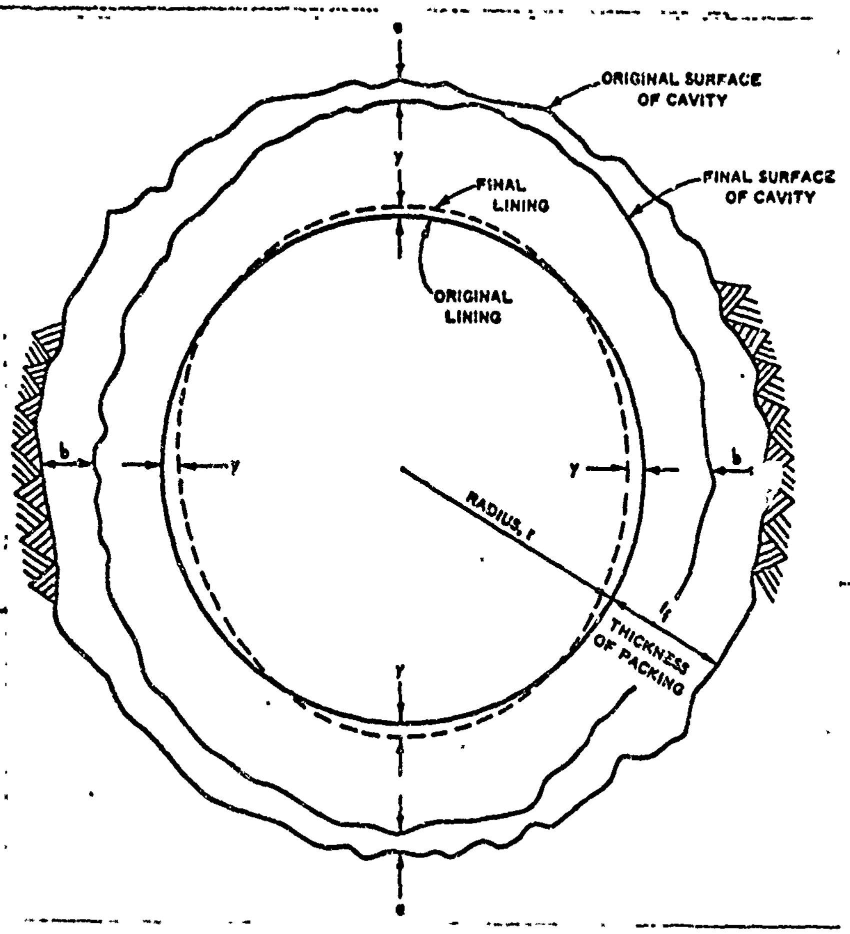

Figure 5. Deformation of lining and packing (Newmark, 15)

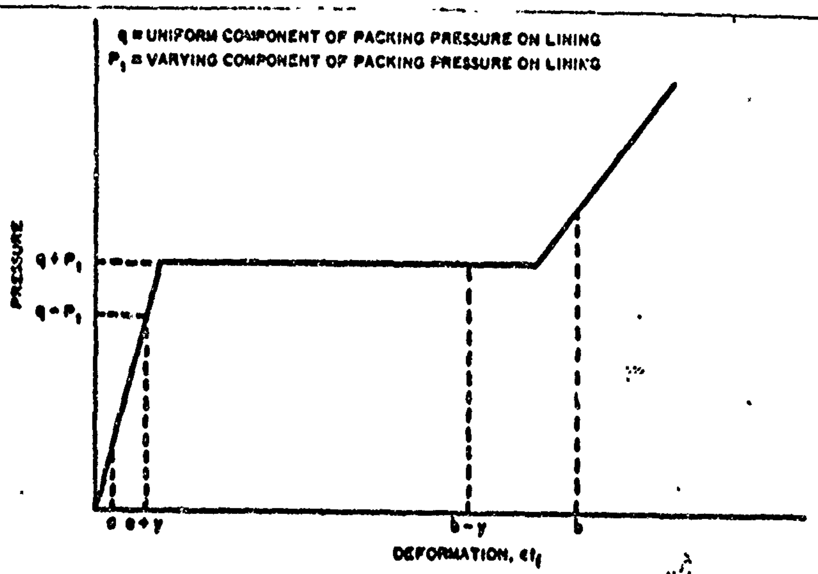

Figure 6. Ideal load-compression relation for packing (Newmark, 15)

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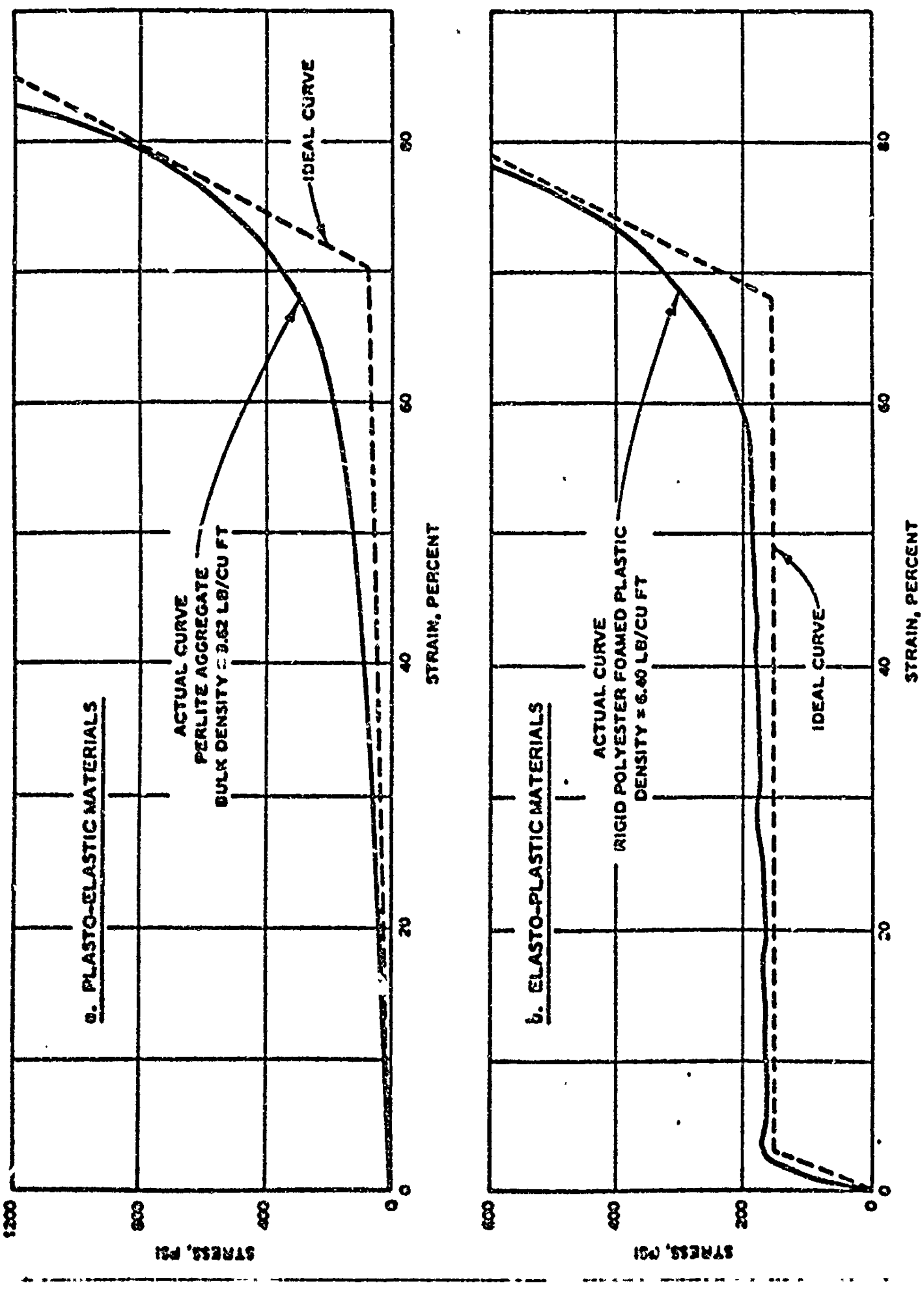

Figure 7. Ideal and typical stress-strain relations

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