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MISSILE BASES: DESIGN AND CONSTRUCTION PROBLEMS

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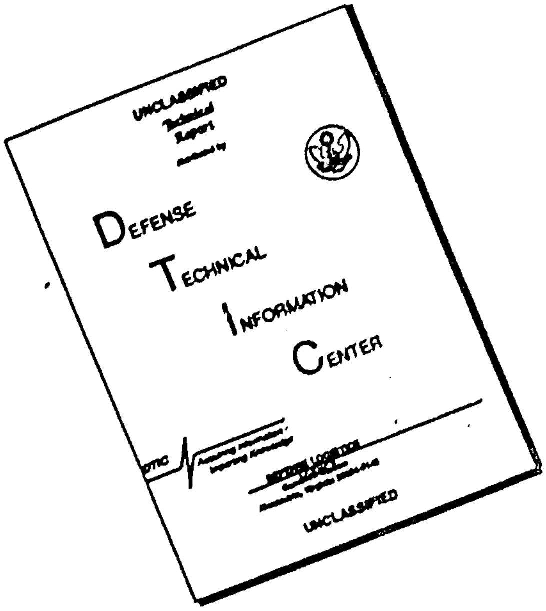
54



FOREWORD

This paper is based principally on reports on missile-base construction problems made by an Office, Chief of Engineers, Soils Investigations Team during the summers of 1961 and 1962. The authors, Mr. W. J. Turnbull and Prof. A. J. Hendron, Jr., served on the team during parts of the field studies.

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COL John R. Oswalt, Jr., CE, and COL Levi A. Brown, CE, were Directors, and Mr. J. B. Tiffany was Technical Director of the Waterways Experiment Station during preparation and publication of this paper.

CONTENTS

MISSILE BASES: DESIGN AND CONSTRUCTION PROBLEMS

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SYNOPSIS

This paper describes the difficulties and problems in connection with design and construction of Intercontinental Ballistic Missile Bases. The problems arose primarily because of (1) the crash nature of the program; (2) the widespread extent areally of facilities in a given missile complex, which resulted in varied geological and water-table conditions; and (3) nonsite adaptation of general plans and specifications for a complex to individual facility sites in the complex.

In spite of harassing design and construction problems which affected the timeliness and cost of construction, all missile complexes were successfully constructed, which involved 850 individual facilities.

INTRODUCTION

The difficulties in design and construction of Intercontinental Ballistic Missile (ICBM) Bases have been recognized and studied for some

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time, although very little documentation of these problems has appeared in the literature. Many of the more serious problems in design and construction arose primarily because of the overall crash nature of the program. This was reflected in excessively short lead time for planning and design, even to the extent of design concurrent with construction, particularly for the earlier missile complexes. Because of the large number and generally widely scattered facilities in the missile complexes, it was very difficult to obtain individual and detailed site adaptation of the plans and specifications. The difficulty was often enhanced by the large variations in the foundation soils within a given missile complex, even though a serious effort was made to minimize these variations in site-location studies. Altogether, about 850 individual facilities were involved in the construction of all the missile complexes; this posed serious design problems from the viewpoint of sheer numbers. This paper should be read keeping in mind the crash nature of the program and that this was the major contributor to two basic deficiencies that are discussed in this paper: (1) lack of time for detailed exploration at each facility, and (2) lack of time for complete site adaptation of plans and specifications. These two basic deficiencies led to many of the other problems that developed.

Realistically, it is believed that very few completely new design problems have been introduced by the missile-base construction work. Instead, by the very nature of the bases, namely, construction below the water table and restriction in areal space, certain design problems have been acutely accentuated and may appear to some as really representing new design problems. On the contrary, the construction of the bases, particularly because of restricted areas, imposed unanticipated difficulties. In other words, excavation and compacted backfill problems in construction were sharply accentuated in the missile-base construction work to the point that they may be regarded as new problems

Purpose

The purposes of this paper are to discuss (1) design problems that are accentuated in missile-base construction, and (2) construction problems, some of which are so acutely accentuated that they may be regarded as new problems.

Scope

The paper deals primarily with design and construction problems of missile-base complexes, namely, Titans I and II, Atlas F, and Minuteman, as they affect the structural integrity under static loading. Secondarily, a portion of the paper treats additional problems in design and/or construction caused by the effect of dynamic loadings.

Basic philosophy of design

The philosophy of design (as construed by the writers) of missile bases of necessity must consider two basic features, the first being structural integrity with respect to static loading, and the second structural integrity with respect to dynamic loading which in effect determines the hardness of the structure. Requirements for structural integrity for static loading are met if the structure, as designed and built, satisfactorily accommodates all deformations, both total and differential, due to all static loadings with adequate factors of safety. The hardness feature considers any additional requirements (over and above those for static loadings) in design and/or construction that are necessary for the structure to successfully resist dynamic loads imposed through blast effects.

The paper is divided into two parts; the first part treats static loading problems, and the second part treats dynamic loading problems.

STATIC LOADING PROBLEMS

Background

General

In order to gain a better idea of missile-base construction work, some illustrations are included which demonstrate why rather severe problems in design and/or construction developed. Figure 1 is an aerial view of a Titan I complex. The view shows the structures partially backfilled, and illustrates the steep back slopes and the relatively confined construction area involved. Figure 2 is a cutaway of the Atlas F configuration showing the location of the major features of construction with respect to the ground surface. Figure 3 is a cutaway of a Minuteman launch facility showing the relation of the launch equipment room (LER) (doughnut-shaped structure around the missile shaft), access shaft (AS), and launch equipment building (LEB). It will be noted that very little of the structure is above the ground surface. Figure 4 is a cutaway showing the Minuteman launch control facility. The launch control equipment building (structure in right of figure) and the launch control center are clearly delineated in this figure. The vertical access shaft is shown tying into a surface structure. Figure 5 is an aerial view of the excavation for a Minuteman facility complex. Excavation is shown to the basic level with no backfill in place.

The construction of all complexes involved excavation to a basic level or levels, the elevations of which were selected for convenient construction of the principal structure foundations. Excavations for shafts and other structures with deeper foundations were made individually below the basic level or levels selected.

The discussion of design problems is separated from that of construction problems, but it is quite difficult to discuss these problems without an overlap one with the other. The writers recognize this but nonetheless have chosen to follow this procedure for reasons of clarity.

Sources of information

The principal sources of information for this paper were the reports on missile-base construction problems made by an Office, Chief of Engineers (OCE) Soils Investigation Team during the summers of 1961 and 1962 (1,2).[3] Turnbull and Hendron served directly on the Soils Team during part of the field studies. Studies were made in 1961 on five Titan I, three Titan II, six Atlas F, and one Minuteman facilities; and in 1962 on three Titan II

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[3] Numerals in parentheses refer to similarly numbered items in the Appendix, References.

and four Minuteman facilities. The reports used were as follows:

1. Reports of a Soils Board investigating general problems of construction at the Minuteman Missile Complex, Grand Forks, N. Dak. (3).

2. Reports of a Soils Board investigating foundation heave problems due to freezing at the Minuteman Missile Complex, Grand Forks, N. Dak. (4,5).

3. Report of inspection of dewatering problems at site 11, Atlas F facility, Plattsburgh, N. Y. (6).

4. Design plan for dewatering site 11, Atlas F facility, Plattsburgh, N. Y. (7).

5. Report of inspection of slide in shales at Titan II facilities, Little Rock, Ark. (8).

6. Ballistic Missile and Space Facility Design and Construction Handbook (9).

Design Problems

Site selection

Many important factors must be considered in locating a missile complex. Some of these factors are topography, general geologic features, specific subsurface soil and/or rock profiles, water tables, cultural development, transportation availability, population density, and sometimes other nontechnical reasons. In the paper, the discussion is confined almost entirely to the geologic and/or engineering aspects of missile-base location, since, to a large extent, they control the design and construction problems that will be encountered. Further, the hardness of a site, that is, the dynamic blast loading considerations, is primarily controlled by the geologic and water-table conditions existing at the site. This will be discussed later.

Explorations

It has often been said that it is impossible to have too many subsurface explorations for important engineering structures; however, there is a limit beyond which exploration in quantity can be carried. Just what this limit is, as far as missile bases are concerned, has not been determined; however, on the basis of the study by the OCE investigation teams, it was apparent that in general the field investigational work could not be considered adequate in all respects. Probably the principal reason for inadequate coverage was the crash nature of the missile-base construction programs. Generally, there was at least one boring, sometimes partially undisturbed, at each facility, usually in the silo area. Sometimes other borings were made at the location of another principal structure or structures of the same facility. An indication of the inadequacy of exploration work is that the general specifications for an overall missile complex could ordinarily not be site-adapted in a completely adequate sense to the individual missile facilities in the complex, even if the attempt were made.

Generally, the borings taken at each facility reasonably demonstrated the general soil and/or rock profiles, water table, and geologic conditions. However, the permeability tests conducted during the boring operations were inadequate to furnish a clear-cut idea on which to base the probable difficulties of the dewatering problem. In the case of clays and clay shales, the true delineation of the water table was often inaccurate.

Laboratory studies

Normally, the OCE investigation teams found the laboratory studies to be reasonably satisfactory. This was particularly true as far as gradation analyses, identification, and ordinary strength tests of the soils were concerned. There was a definite need for more studies which would indicate the engineering behavior of the materials, such as slaking, permeability, and plasticity tests. The slaking tests are considered important in that a better estimation could have been made concerning the behavior of steep slopes under various environmental conditions including wetting and drying and freezing and thawing. More careful permeability testing, particularly of the in situ materials, was desirable to obtain a better idea of the quantity of water involved in developing an adequate drainage system and specifically in determining the type of system needed. The plasticity or Atterberg limits tests were necessary, particularly in glacial-type soils, in order to develop in advance the best information possible concerning the danger of piping failure of slopes and/or the development of pore pressures which might result in partial or complete liquefaction of soil layers as excavation proceeded.

Plans and specifications

Usually, the OCE investigation teams found the general plans and specifications to be reasonably good. For instance, the specifications required the contractor to submit plans of excavation, dewatering, and backfilling for specific sites in advance of accomplishing the work. In essence, such plans called for site adaptation, following the outline of the general plans. Quite often, follow-through by the engineer for the Government was not sufficient to cause the contractor to submit such plans, particularly for dewatering; thus, many subsequent difficulties developed.

There was an annoying problem, particularly in connection with the Titan I bases. These bases required relatively long lengths of underground, interconnecting tunnels partially or completely below the water table. The tunnels were made up of multiplate corrugated steel pipe and were usually fabricated in sections on the ground surface before being lowered into the tunnel excavation area. The plans and specifications called for the joints to be watertight, yet furnished no details concerning how this should be accomplished. The contractor, in buying and assembling the multiplate, apparently made no effort to seal the joints when assembling the plates; this was also overlooked by the engineer. The net result was that in some facilities detrimental leakage was encountered that later resulted in harassing delays in time due to required repair measures after the tunnel pipe was in place. This entire procedure seemed uncalled for in view of the fact that for many years prior to this time methods of sealing underground pipe were in existence. Figure 6 is an interior view of a multiplate steel tunnel showing the many joints and connecting-bolt holes where possibilities of leakage existed.

Another difficulty caused by the failure to recognize the effects of site adaptation in the plans and specifications was that structure requirements for a given set of geologic and water-table conditions might be different in some basic concepts for other conditions, but such differences were not recognized in the design. In some of the missile complexes, due to the wide dispersion of facilities, variations in soil and/or rock types, water-table conditions, and other important factors occurred from facility to facility. This condition was not recognized in design.

Structure design

Problems between the structural designer and the foundation engineer are not new, but they were intensified in the design of structures for the Intercontinental Ballistic Missile Bases. Most of these problems were related to allowable total and/or differential settlement of structure foundations and the effects of such settlements on structural requirements, both horizontally and vertically. Any foundation settlement that would adversely affect the behavior of the structure under static loading should be placed in the category of a structural design problem. For instance, differential settlement under the LER surrounding the missile shaft of the Minuteman facility could adversely affect the required lateral clearance between the shaft and the LER. Another instance of settlement affecting the integrity of a structure would be settlement of the sight tube of the Atlas F silo.

A definite need has always existed, which was emphasized by the missile construction work, for the structural designer to be more realistic in structure design for static loads regarding the amount of total or differential settlement that the structure can be designed to tolerate. Unrealistic design requirements in this respect tend to add greatly to the difficulties and cost of construction. It was felt that, in general, the structure, as designed, could tolerate more settlement than the designer admitted; further, the designer could have improved his design so that the structure could have survived even more settlement without damage under static and dynamic loadings.

Construction Problems

Contractor

In general, the capabilities of the various contractors engaged in missile-base construction work were not questioned. Equipment furnished was, as a rule, considered satisfactory. One of the principal weaknesses of the contractor group was not preparing plans for dewatering and submitting them in advance to the Government engineers. In a sense, due to failure to recognize the effects of nonsite adaptation of the general plans and specifications, this type of work placed the contractor in the position of doing work ordinarily accomplished by an owner design group. Probably quite often the contractor did not have people in his organization who were capable of designing a dewatering system. Such work could probably have been better accomplished through more detailed site adaptation by design engineers.

The contractors generally submitted a reasonably good advance plan for excavation, except for the fact that there was a tendency to ignore critical factors because a proper dewatering plan had not been developed, and therefore the ill effects of improper dewatering on excavating had not been recognized. The plans for backfilling submitted by the contractors were usually deficient regarding the details for compaction in those small areas difficult to get to even with hand-operated mechanical compaction equipment. These areas almost without exception required good compaction, since they were critical with respect to differential settlement of important parts of connecting structures. In this paper, they are deemed as areas "critical" to compaction. Volumewise, they probably do not represent more than 10 percent of the total compacted yardage.

In one instance, at a missile complex, the contractor constructed a model of the missile facility to aid in solving the problem of pipe and structure layout in order to facilitate the placement of backfill around them. This was very helpful, and such initiative on the part of the contractor was commendable.

Government engineer-inspector (EI) group

Again, the failure to recognize the effects of nonsite adaptation of the plans and specifications during the design phase was the cause of material difficulties experienced by the Government EI group in obtaining the best results. Particular reference here is of course to the dewatering problem. In some instances, the contractor was allowed to proceed before he had submitted his plans for excavating, dewatering, and backfilling (inadequate as they were). Obviously, this led to considerable trouble as the work progressed.

One of the principal problems of the Government EI group was the lack of a sufficient number of trained inspectors, which was made much more acute by the large number and wide areal dispersion of the facilities. In some instances, it was impossible for a qualified inspector to visit the job more than once a day and then only for a short time. Also, lack of communication entered into the problem. This lack of communication existed between the field and office forces and, in turn, the office forces lacked communication with the basic design group in the area or district office in question.

It was noticeable to the OCE investigation teams that where the chief of the Government EI group had a real appreciation of foundation problems, better cooperation was secured with the contractor; consequently, the problems that developed were of a less severe nature. It was also quite noticeable to the OCE investigation teams that better work was obtained at those missile complexes where the Government construction engineer maintained close liaison between the area laboratory and the field forces.

Construction control

Basically, it was considered that where difficulties were experienced in construction control, requirements of one or more of the following items were violated.

1. Delineation of all critical areas of backfill and dissemination of this information to all personnel associated with construction control.
2. Proper training of earthwork construction-control personnel, with special attention to hand-compaction operations in the critical areas.
3. Organization of a construction-control force to assure reasonably constant inspection of all backfill and compaction operations.
4. Making available to the individual construction sites at the time of backfilling the necessary items of testing equipment for construction-control operations.

The reasons for inability to meet the requirements of any of the four items could generally be ascribed to:

1. Inadequate plan for backfilling.
2. Improper stockpiling during excavation.
3. Improper moisture control including the operation of adding or deleting moisture from the soil.
4. Inadequate inspection force both as to quality and quantity.

5. Poor communications and cooperation between construction engineers and the contractor with respect to proper time-phasing of the backfilling of the various structures, tunnels, and conduits.

6. Lack of ingenuity of the engineers and contractor in devising or obtaining proper compaction equipment where hand-compaction or hand-operated machine compaction was necessary in the critical areas.

Physical factors

Each missile complex usually had some unique physical factors or was subjected to an environment that in too many instances had significant effects on structures. Some of the most prominent of these were extremely cold weather and extended periods of cold weather, very sudden drops in temperature, drifting snow, elevation of groundwater, availability of water for compaction control, great variations in soil or rock materials encountered at individual facilities in a given complex, and the wide areal dispersion of facilities in a complex.

In spite of possible adverse effects of physical and environmental factors, it cannot be said that these were the controlling features leading to construction difficulties at a given facility or in an entire complex. Instead, factors which were outstanding in favorably or detrimentally affecting the constructing of a facility were advance planning, correct evaluation of physical and environmental factors, cooperation between engineer and contractor, quality and quantity of inspection forces, and recognition and utilization of previous construction experience.

Construction operations

This topic is so broad that it is believed more appropriate to discuss various items that are pertinent to construction operations on an individual item basis.

Excavation. The lack of adequate plans and specifications for individual facilities, as far as excavating and dewatering were concerned, can be considered as the basic cause of many difficulties. Excavation, in general, both in open cut and shaft, posed relatively few problems except in those sites where unanticipated difficulties were produced by groundwater or where improper blasting techniques were used. It was the exception rather than the rule for groundwater problems to be properly evaluated in advance of construction and for proper construction techniques to be utilized to avoid difficulty. In fact, at numerous facility sites, it was not possible to develop proper construction techniques due to the absence of a properly designed and installed dewatering system. Improper handling of groundwater resulted in sloughing of slopes that were excavated too steep; development of high pore pressures in cohesionless materials around shafts, causing excessive lateral pressures and sometimes outright failures; slippage of rock, shale blocks, and soil into shafts; and development of quick conditions in areas being excavated due to seepage into the completed excavation. Figure 7 shows an Atlas facility with excavation to the basic level; water problems are being experienced from runoff into the excavation and from seepage at the toe of the excavation. Figure 8 is a view looking into an Atlas F silo showing a wet, mucky condition at the bottom of the excavation. Figures 9, 10, 11, and 12 are views of Minuteman excavations. Figure 9 shows a wet base-level excavation due to seepage from the toe of the slope. Figure 10 shows water piping from the toe of the excavation and sloughing soil. Figure 11 shows the completed excavation for an LEB structure, the bottom of which has become liquefied due to upward seepage. Figure 12 shows excavation for the AS structure filled with seepage water.

All the conditions demonstrated by the preceding six figures were harassing, costly in terms of time and money, and affected the as-built conditions and settlements.

One of the very annoying problems that developed occasionally and that could have easily been prevented was flooding of the excavation from surface rainfall.

The standard specifications for one type of missile complex required that experimental blasting be accomplished by the contractor in order to determine proper procedures to follow in excavations. This was very seldom done, and the result was that too often detrimental effects developed from the lack of blasting knowledge, such as overexcavation or unnecessary loosening of the material back of the neat line of excavation.

Another annoying excavation detail was that at some facilities adequate ramps were not provided to haul backfill material into the excavation; instead, the material was pushed over the edges around the periphery of the excavation with a tendency toward segregation of the backfill material.

A particularly costly error at one complex was that the bases of slopes and the foundations of structures were, in many instances, inadequately protected from freezing and thawing. The result was unnecessary sloughing of slopes and heaving of the structure foundations.

Stockpiling. The specifications required stockpiling of excavated materials by segregation with respect to the major classes of backfill and those materials that were to be wasted. In most instances, this was satisfactorily accomplished; however, on occasion, basic classes of backfill were mixed with waste material to the extent that time and expense were involved either in attempting to handpick the stockpile for backfilling or select completely new sources for proper backfill material. In either instance, obvious additional costs in time and money were involved. Generally, the stockpiles were shaped to drain; however, on occasion, water collected in ponds on top of the stockpiles, resulting in difficulty in selecting and processing the backfill. Processing of moisture into or out of the backfill material should be accomplished on the stockpile, and was to a great extent; however, sometimes this was not done and difficulty was experienced in attempting to process moisture into or out of material after it was hauled and placed in lifts in the relatively small open areas around the structure.

Backfill material and compaction. Backfill deficiencies or potential deficiencies for both noncritical and critical areas were obvious at every missile complex visited. Those deficiencies that were most common were:

(1) Failure to have an approved detailed backfill plan, particularly with respect to critical areas.

(2) Lift thicknesses consistently too great for the equipment being used and thicker than permitted by the specifications.

(3) Processing on the fill for removal of oversize stones.

(4) Backfill slopes much too steep at many sites.

(5) General surface unevenness on most fill areas. This meant that both fill placement and compaction were progressing without uniform, well-defined patterns.

(6) Segregation of coarse stone in the backfill materials.

(7) Occasional use of compaction equipment not well suited to the soil type being compacted, particularly in the critical areas.

(8) Adjustment of moisture content after material was moved to the fill area.

(9) Improper material selected for backfill in critical areas.

Very few problems developed in the nonrestricted (noncritical to compaction) areas of the excavation where full-scale compaction equipment could be used by the contractor. Further discussion pertains specifically to those critical areas restricted in areal extent where hand compaction had to be used or where, by very careful movement, ordinary compaction equipment could be utilized.

In most instances in the closely restricted areas, both horizontal and vertical, some type of mechanical hand compactor was used. Restricted areas (critical to compaction) were produced by structural configurations, such as under the haunches of tunnels and pipes of varying diameters, connections of pipes and tunnels into silos or other underground structures, and between steep backslopes and the structure wall. Figure 13 shows the backfill around a concrete blast-lock structure and below the haunch of the pipe of the connecting steel-plate tunnel at a Titan I facility. Figure 14 shows the restricted backfill area around the access portal and appurtenant structures at a Titan II installation. Figure 15 illustrates the constricted areas at a Minuteman facility around the LEB and appurtenant connecting facilities. This figure graphically illustrates the importance of compacting around piping (note the lower midportion of the picture) before general backfilling commences in the area. The figure shows uncompacted material that has slid in around the pipe and will have to be reexcavated or it will be buried when general backfill operations start, thus covering up defective work. The lower right of the figure illustrates a vertical-sided excavated area that must be carefully backfilled.

The selection of proper backfill materials had a large bearing on the difficulties encountered; for example,

(1) Materials with aggregate in excess of 4 in. were very difficult to handle and compact in critical areas.

(2) Certain materials, if improperly handled, tended to segregate.

(3) Highly plastic clays could not be effectively placed in critical areas.

(4) On occasion, frozen materials were used in backfill and caused costly settlements.

Probably the most outstanding example of detrimental settlement due to placement of frozen material was the behavior of the vestibule that connected the tunnel to the silo shaft in an Atlas F facility. At this site, the vestibule settled as much as 12 in., and this of course resulted in completely ineffective use of the blast doors and in costly reconstruction measures. More will be said concerning settlements as they affect dynamic design requirements in the second part of this paper regarding the dynamic loading problems.

Dry sand-gravel was hauled in and utilized for backfilling in critical areas at some facilities, and adequate compaction was obtained much easier than with most other materials.

The improper cleanup of the backfill areas before introducing the backfill material was sometimes the cause of excessive settlement.

In one instance, this was known to contribute to a very serious leakage which could have resulted in a blowup of the bottom of a facility in one of the Atlas F complexes. Another instance noted by the OCE soils team was the covering up by compacted fill of an area that was filled with loose soil and waste debris under a tunnel at its junction with a structure. If this had slipped by the Government inspector, little or no soil support would have been provided for about the first 6 ft of the tunnel from the structure wall. Internal inspection of the completed backfilled structure always indicated a tendency toward greatest settlement and distress at points such as the one just described or at similar critical areas. This behavior indicated that in many instances adequate compaction at these critical areas was not obtained.

The backfill problems at the missile facilities were to a large extent created by the critically restricted areas. As previously mentioned, these restricted areas are only a small part of the total excavation to be backfilled, probably not more than 10 percent volumewise. It is believed that if the critical areas had received the major attention and the noncritical areas only minor attention, then the overall problem of backfill would have been handled more timely and economically.

Significant Causes of Design and/or Construction Problems

The following brief discussion is an attempt to summarize the causes and reasons why design or construction problems developed, some of which assumed major proportions.

Lack of site-adaptation of plans and specifications

It has already been stated that largely due to the crash nature of the missile-base construction work, proper site-adaptation of the general plans and specifications was not made. In some instances, this could have been done; but in other instances, it was not possible because of lack of adequate exploration. All too often, it was not done due to lack of recognition that the foundation conditions known to exist would affect structure design and construction procedures. The authors believe that the basic lesson that can be learned from the lack of site adaptation is that the owner, namely, the Government, should have more fully accepted the responsibility for determining the requirements for dewatering. It is believed that, even though in certain cases adequate information was not available, better dewatering systems than were used could in most instances have been designed and utilized and would have resulted in more timely and less costly construction; thus, the principal cause for overruns in cost and time in the missile-base construction work would have been eliminated.

Lack of "upstream" construction experience

As previously mentioned, the missile-base construction work caused certain design and construction problems that have always existed to become quite acute. The severity of these problems to a large degree was caused by the fact that very little experience in missile-base construction existed. The design and construction of a good many of the later facilities of the various types benefited from the experiences gained in earlier work; this was quite noticeable to the OCE investigation teams.

Improper evaluation of foundation conditions

The improper evaluation of foundation conditions, leading to the dewatering and back-slope problems, has already been mentioned. One other serious problem that developed quite often was that of recognizing that a cohesionless fine-grained soil under the water table could develop detrimental construction features, such as piping, high pressures back of lagging in shaft excavation, liquefaction, etc. These soils possess an inherently high shearing strength in situ; but when disturbed, with a tendency toward consolidation, they developed some of the adverse characteristics mentioned.

Nonrecognition of factors conducive to construction difficulties

It was obvious in numerous instances that the plans and specifications and construction procedures adopted did not recognize inherent properties of soils and existing geologic conditions that would lead to construction difficulties. For instance, the behaviors of a fairly stable clay shale and a glacial-till silty sand material below the water table would present distinctly different problems for tunnel construction, but this was generally not recognized in design and construction. Similarly, differences often were not recognized in design and construction requirements for shaft excavation in clay shales, glacial sands, and rock masses below the water table.

Improper site considerations for adequate structural design

Here again, problems are directly attributable to the failure to recognize the effects of the lack of site-adaptation in plans and specifications. For example, a Minuteman complex consists of dozens of facilities, each of which in itself is an expensive and costly structure. Even though, in site selection, efforts were made to obtain uniform geologic conditions throughout a missile complex, they largely came to naught, since the complexes extend areally over many miles (40 to 100 miles). The soils involved in some areas ranged from sandy till to shale and rock. It is thus obvious that if one facility of a complex were built in rock, it should have certain basic differences in design from a similar structure built in glacial-till sand, and different construction problems would be involved.

DYNAMIC LOADING PROBLEMS

Background

Protective structures, such as the Atlas, Titan I, Titan II, and Minuteman missile systems, were designed to provide sufficient structural integrity such that the structures could resist the dynamic loads without collapse or excessive deformation. In addition, the design of shock-isolation systems was necessary to prevent damage or injury to the missiles, electronic equipment, and personnel. The stress-strain properties of the soil medium influenced both phases of the dynamic design delineated above. Therefore, site selection determined to a great extent the dynamic loads to be resisted and the ground motion to be tolerated by the missile systems described in this paper. Construction details or procedures necessary for static structural integrity, which most affect the soil properties in the immediate area of the completed structure, also influence the dynamic behavior and hardness of the structure. Because the static behavior of the structures is also dependent upon the in situ stress-strain and strength properties of the soil, it is generally true that construction procedures and details which are more desirable for the performance of the structures under static conditions are also more desirable for the dynamic behavior or hardness of the structures. Therefore, experience established by the design, construction planning, and inspection of conventional excavations, foundations, and backfills represented a body of knowledge which could be used to advantage in the design and construction of the ballistic missile systems.

There was a tendency in design and construction work to overemphasize possible dynamic problems at the expense of static problems such that full advantage was not taken of prior experience gained in static construction. In reality, most of the problems encountered were concerned with the practicality of building the systems to the tolerances specified and keeping the relative settlements and leakage and other critical factors within tolerable limits under the static environment.

Design Considerations

The dynamic designs of the protective structures considered in this paper were primarily governed by the airblast loading and airblast-induced ground motions. Direct ground-shock effects emanating from the crater were considered of minor importance.

Structure

The proportions of various structural components were designed on the basis of the dynamic loads assumed to act on the structure in addition to the static loads and the allowable deformations the structure can undergo without failing to function while resisting the dynamic forces. Normally, the forces for which a blast-resistant structure must be designed are very large in comparison to conventional engineering requirements. Because these loads are of a transient character and their probability of occurrence is small, the proportions are determined on a limit design approach in which the full resistance of the structure is mobilized. Brittle types of failure are avoided, and plastic distortions of structural elements may be permitted at the design loads for many structures. For some structures, however, it is important to minimize cracking and limit deflections or distortions; in these cases, it may not be possible to develop the full strength of the structure or member under dynamic loading.

The forces for which a protective structure must be designed may originate directly from the airblast, as in the case of the overpressure loading on the Minuteman LER shown in Figure 16. In addition, the strains in the backfill material result in relative movements between the backfill and the LER which mobilize the undrained shear strength of the soil as shown in Figure 16. Although the shear strength is mobilized under dynamic loading, the same strength can be mobilized under static loading in the case of a consolidation tendency in poorly compacted backfill. Thus, in the dynamic case, the walls of the LER, for example, would be designed to resist the load applied to the blast door, the shearing stresses developed at the sidewall interface between structure and soil, and the radial stresses P_L which are taken as some fraction of the vertical stresses. The structural design to resist these loads is not a difficult problem.

Structure-soil relation

A more difficult problem in the structure used as an example (Figure 16) is limiting the relative displacements and rotations between the LER and the launch tube to reasonable values by the selection of an appropriate footing width. The most difficult problem in the dynamic design for structural integrity involved connections to the structures or between buried structures which would be subjected to distortions due to the possibility of relative displacement between the soil backfill and the structure or relative displacements between structures. The magnitude of these relative displacements is dependent upon the strains which develop in the soil above the base of a structure to which appurtenances and connections are attached. If the backfill above the base of the main structure is compressible, the connection may be sheared off during dynamic loading if the differential static settlements had not previously severed the connection. Therefore, although the dynamic relative displacements were important factors which had to be considered for the design of connections and appurtenances between structures; the main factors which in reality control the dynamic relative displacement are the same soil properties and foundation conditions which control the differential movements and settlements under static conditions. Therefore, the dynamic design did not require construction control materially different from that required for ensuring static integrity of the same structure.

Shock isolation

Again referring to Figure 16, the design of the shock-isolation systems for the missile-mount equipment and personnel in the LER and the LCC require estimates of the free-field ground motions produced by the airblast input. The ground motions from which the missile must be isolated by the shock mount are governed by the dynamic stress-strain characteristics of the materials below the base of the launch tube. Therefore, the motions for which the missile mount had to be designed and rattle space provided were primarily governed by siting and could not be influenced by construction details or procedures. In the case of the Minuteman LER, however, the motions are governed by the free-field motions at the level of the footings in addition to the additional sinkage of the footings with respect to their original position before dynamic loading. Thus, the preservation of an acceptable in situ material or excavation of a poor material for replacement with a select backfill was necessary below the footings in order to minimize the velocity and displacement of the LER structure produced by the airblast. Again, the construction control necessitated by these requirements was not different from those which would be required to successfully construct the same structures for the static environment.

Rattle space

The dynamic design also dictates the rattle space required in the structures with shock-isolated equipment and personnel. Although the rattle space required may be calculated in the design and provided for in the structure, differential settlements and rotations occurring during construction and during the as-built static environment may reduce the rattle space such that structural modifications are necessary. Thus, construction details and procedures which minimize static movements keep the dynamic rattle-space requirements from being infringed upon; in this respect, the designers must be realistic and allow for ordinary differential settlements commonly experienced in good quality construction work. The excavation of material to base levels, excavation for shafts, the construction of facilities, and the subsequent backfilling operations all tend to produce disturbances of the in situ materials and/or lack of uniformity in the backfill which result in certain inevitable differential movements, even if the best construction procedures are followed. Field measurements of a large number of missile facilities suggest that 1/4-in. differential and 1-in. uniform settlement are realistic and should be allowed in the design. These figures are based on the behavior of 850 acceptable facilities.

Construction Problems

Construction problems will not be discussed in detail in that they are, to a large extent, common to both the static and the dynamic structural integrity. Detailed discussion pertaining to the static structural integrity appears earlier in this paper. Construction and control problems involving the backfill immediately under connections to major structures and appurtenant structures connected directly to major structures become particularly critical as far as dynamic loading is concerned. Realistically good construction practice should be supplemented by designing certain flexibility into connections and appurtenant structures. Probably the most critical construction backfill problem with respect to dynamic loading was the degrading of in situ stability of foundation materials due to disturbance caused by overexcavation or detrimental effects of seepage into the structure foundation. As previously indicated, the use of granular materials for backfill in critical areas would have largely eliminated the problems which developed.

CONCLUSION

A large-scale construction program of ICBM bases was successfully accomplished in spite of the crash nature of the program. It was obvious, however, that more economical and timely construction would have been obtained if certain design improvements had been made and requirements met. A greater contribution to the costliness of the program than the design problems was brought about by improper construction techniques and procedures.

More specifically, it is believed that the plans and specifications were reasonably adequate, except inasmuch as they were affected by certain design deficiencies. Nonsite-adaptation of the general plans and specifications to specific facilities in a missile complex was an outstanding contribution to difficulties which arose. It is also apparent that the design phase must not only include proportioning structures for the dynamic loads but should also be concerned with ensuring that construction procedures over and above those necessary for satisfactory static structural integrity be followed, if necessary, for dynamic structural integrity.

The principal reasons for the more costly construction problems are delineated in the text. Suffice it to say, most of them would have been eliminated if high-quality construction techniques gained from prior experience had been followed throughout. In general, many of the construction problems encountered could have affected the dynamic performance of these structures if they had not been corrected.

In general, the difficulties imposed by dynamic design and construction requirements were not greatly significant over those for static requirements.

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Fig. 1. Aerial view of Titan I complex

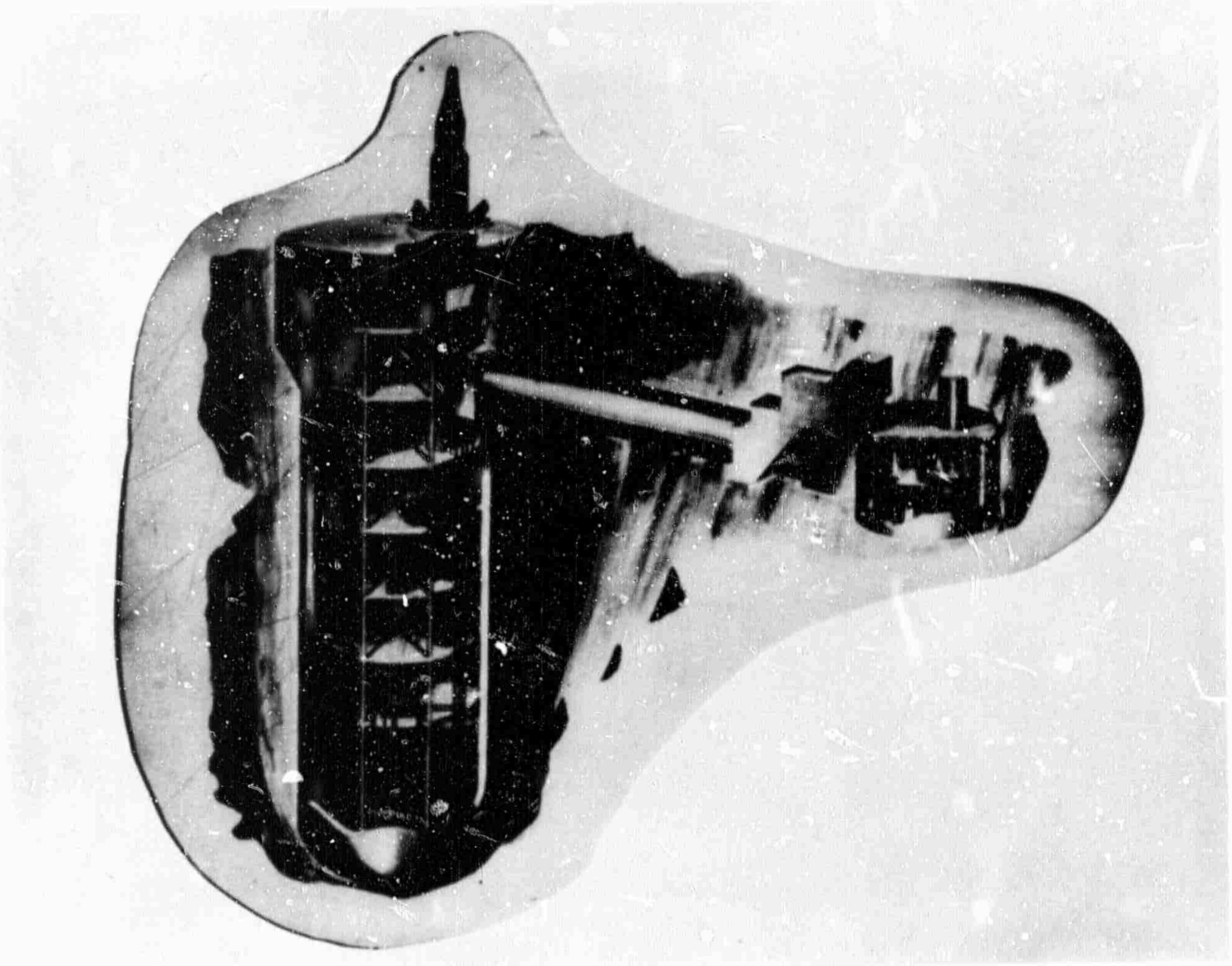

Fig. 2. Atlas F configuration; location of major features of construction with respect to ground surface

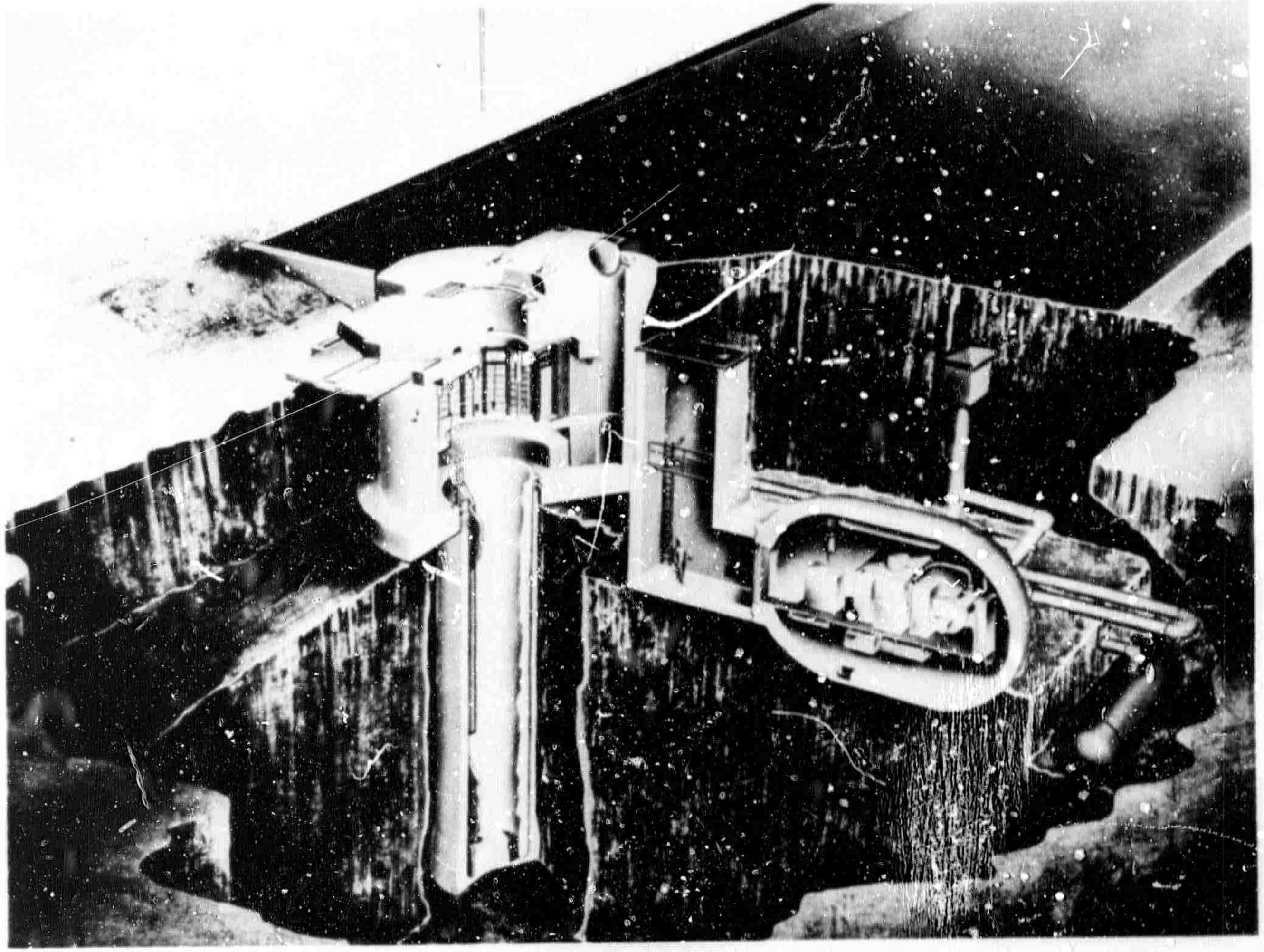

Fig. 3. Minuteman launch facility; relation of launch equipment room, access shaft, and launch equipment building

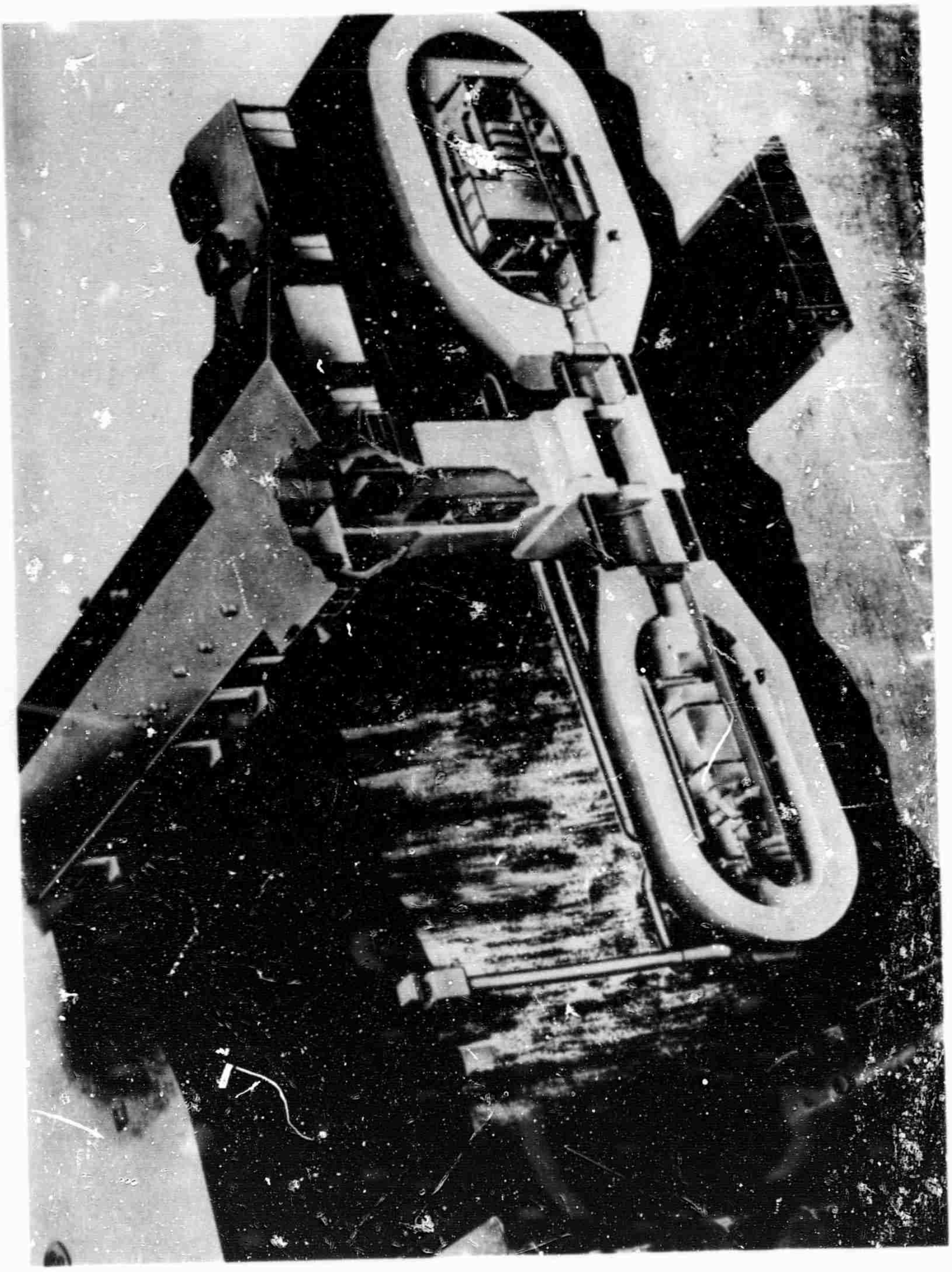

Fig. 4. Minuteman launch control facility

Fig. 5. Aerial view of excavation for a Minuteman facility complex

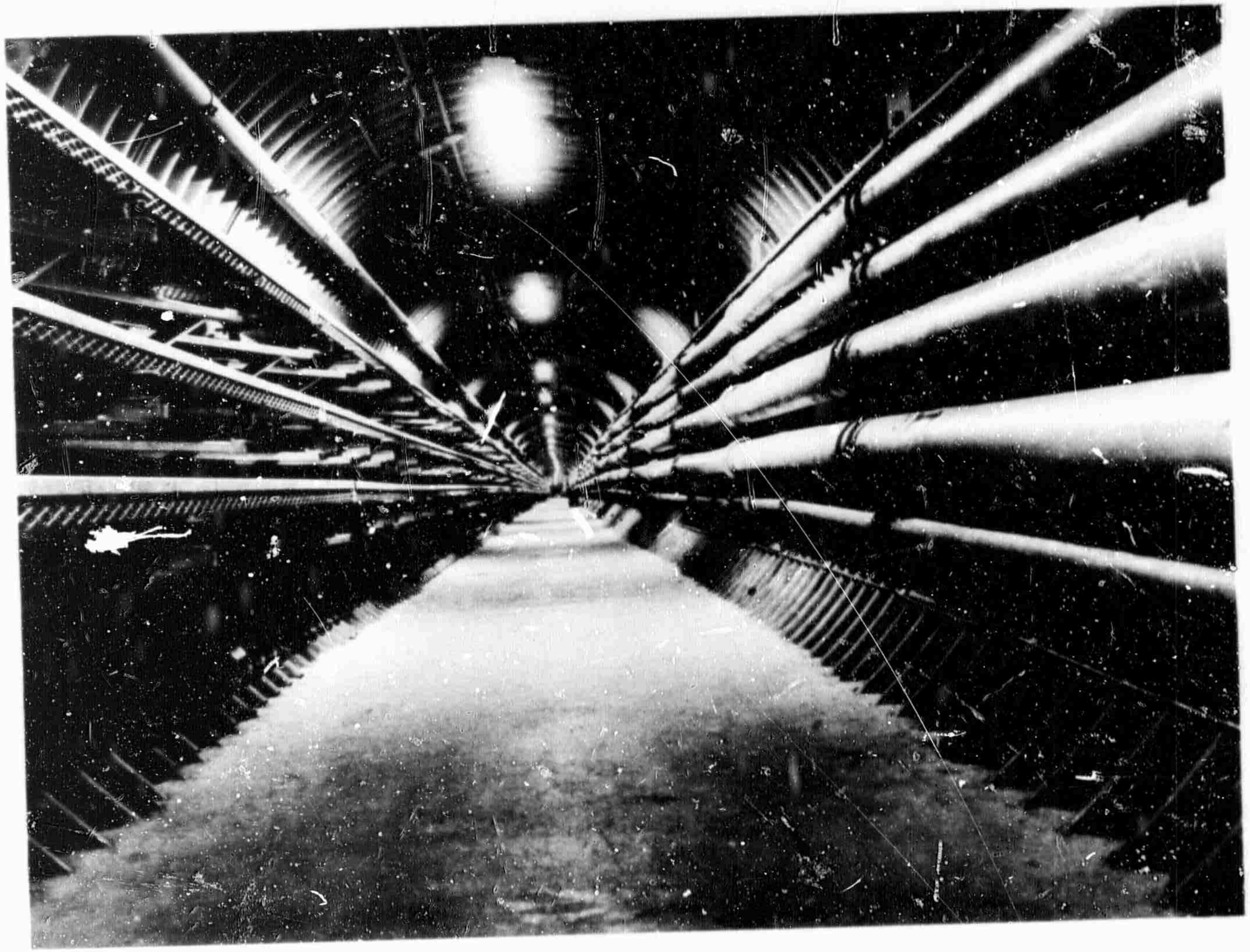

Fig. 6. Interior of a multiplate steel tunnel at a Titan I base

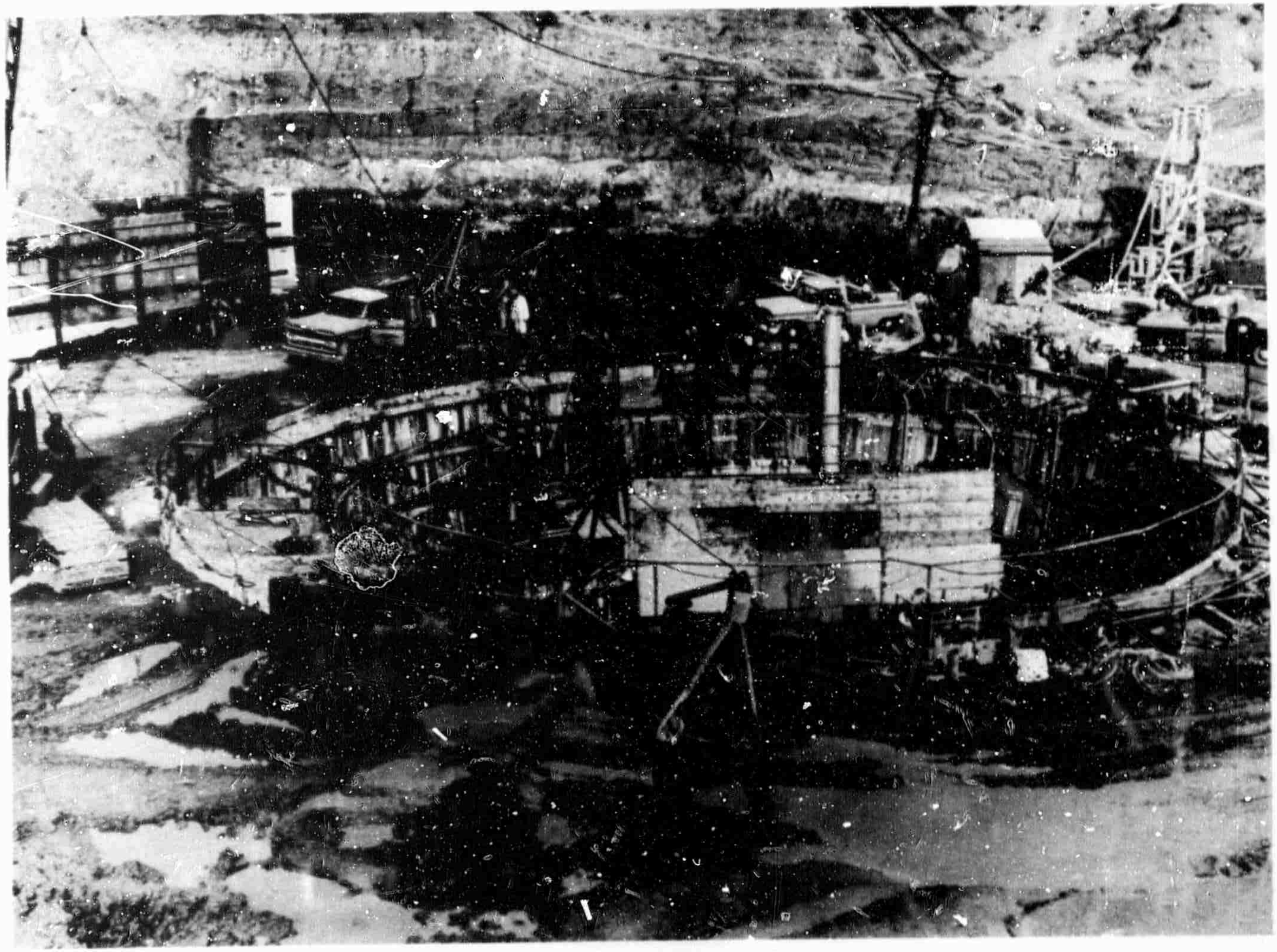

Fig. 7. Excavation to the basic level for an Atlas facility

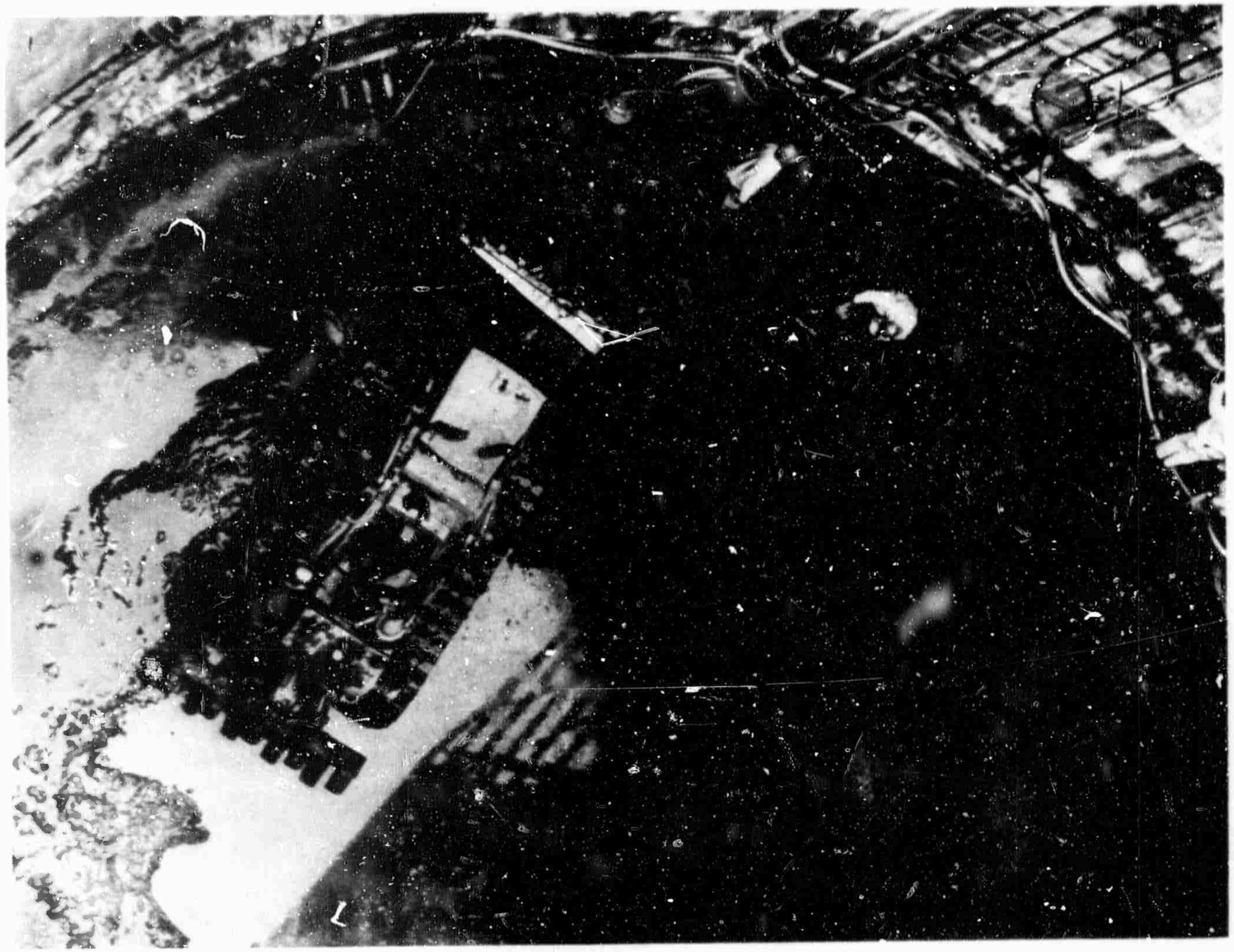

Fig. 8. Bottom of excavation of an Atlas silo

Fig. 9. Minuteman excavation; wet base-level due to seepage from toe of slope

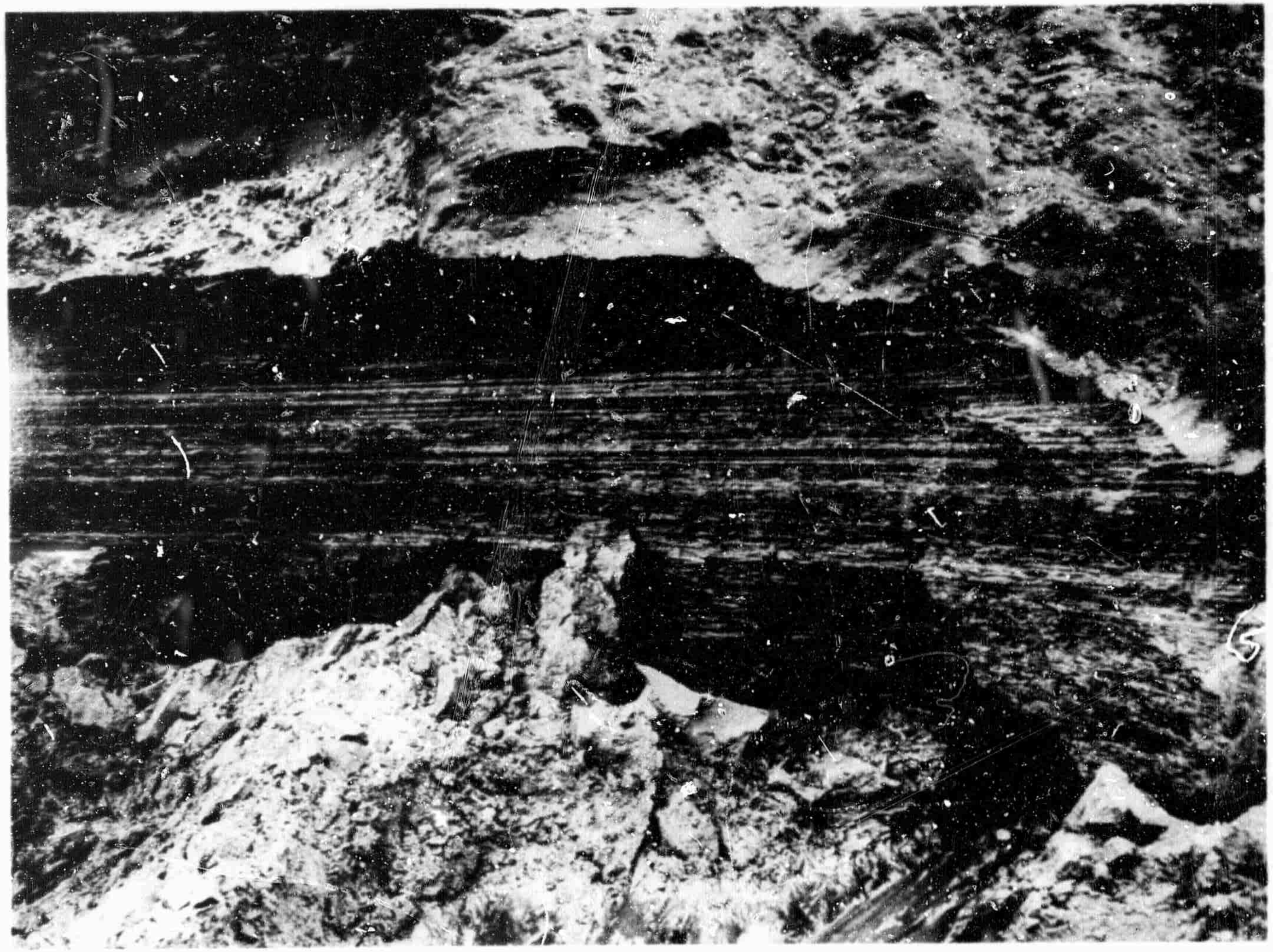

Fig. 10. Minuteman excavation; water piping from toe of excavation and sloughing soil

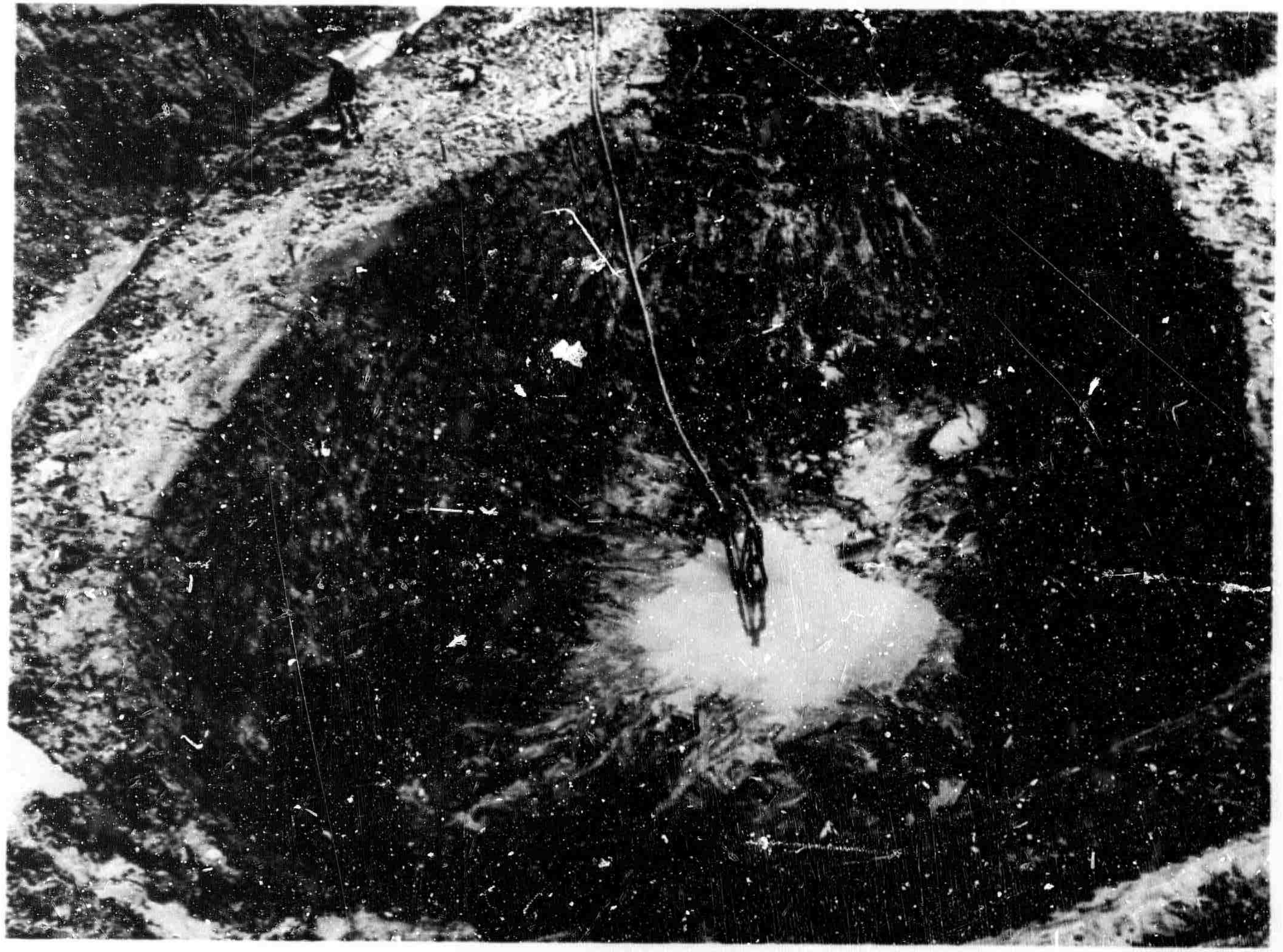

Fig. 11. Completed excavation for Minuteman launch equipment building

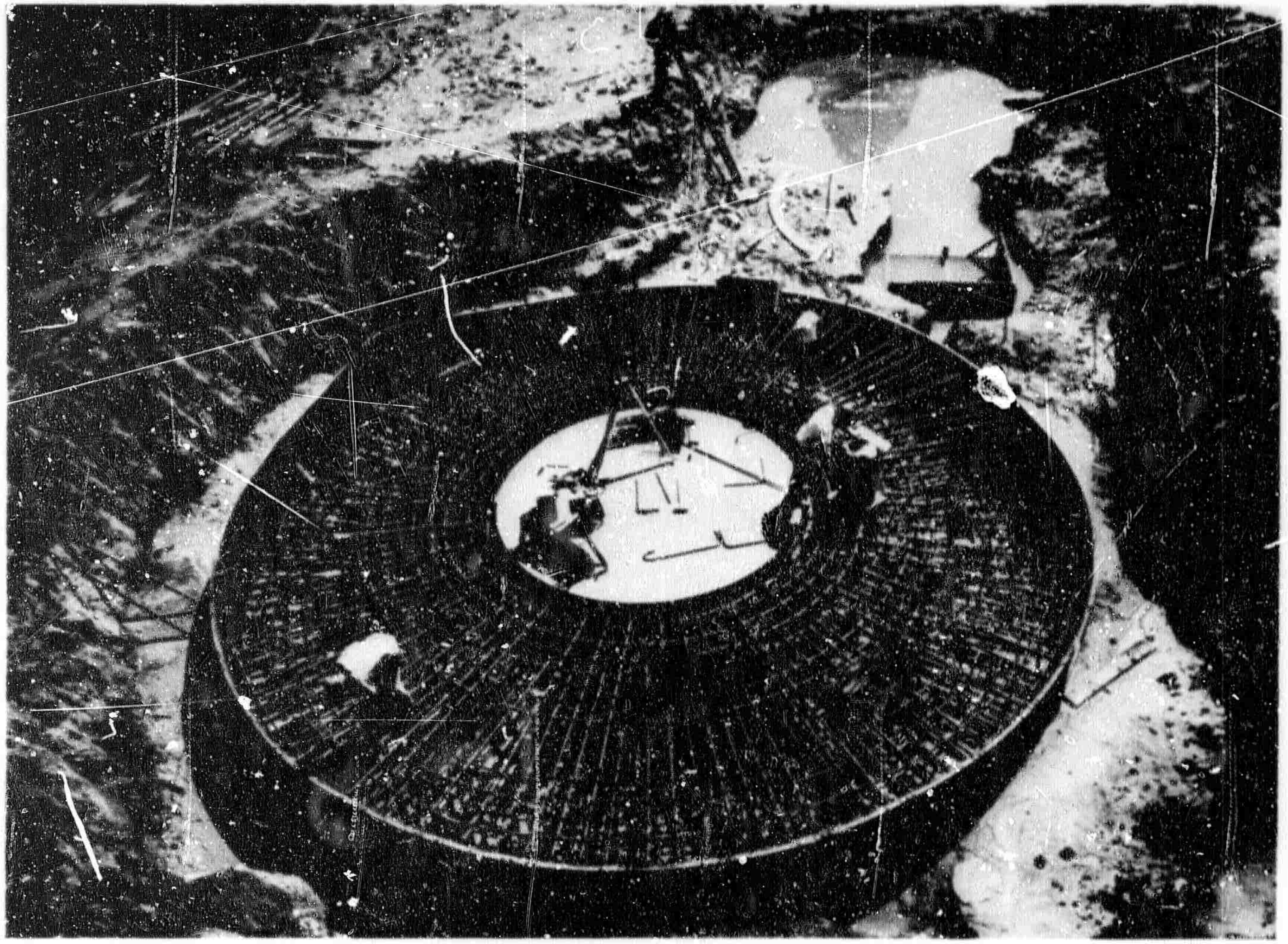

Fig. 12. Excavation for Minuteman air-shaft structure filled with seepage water

Fig. 13. Backfill around concrete blastlock structure and below haunch of steel-plate tunnel, Titan I facility

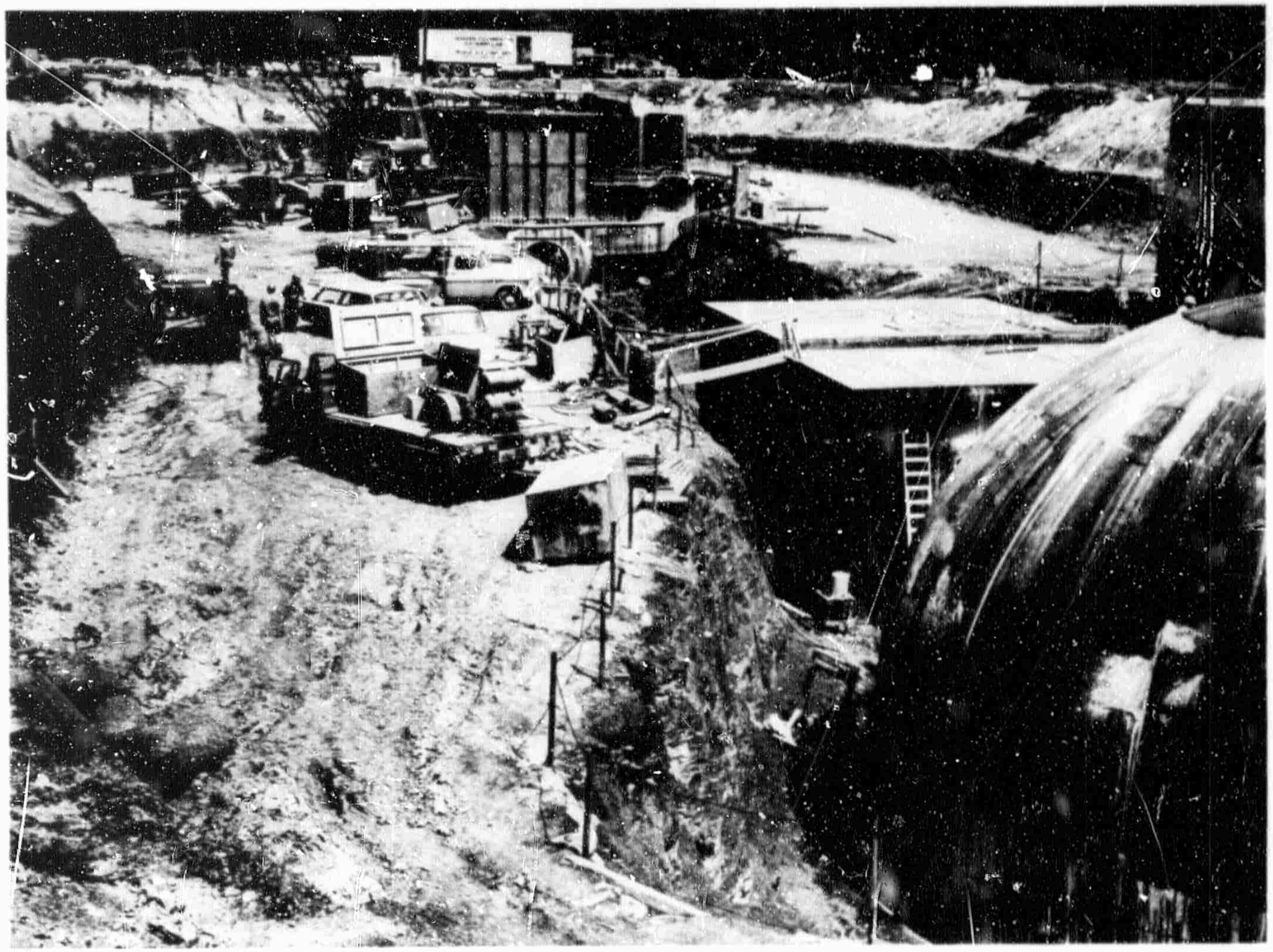

Fig. 14. Restricted backfill area at a Titan II facility

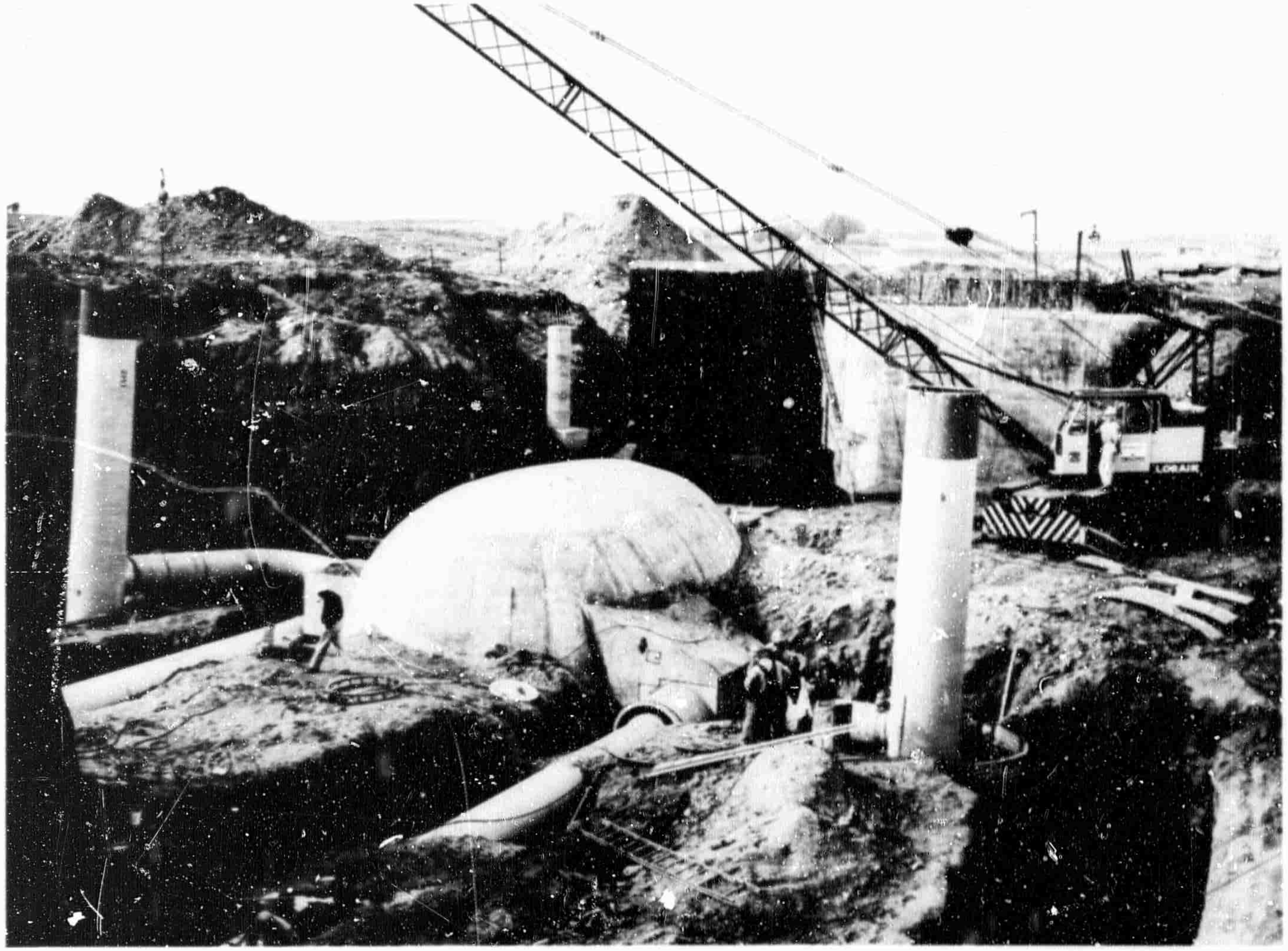

Fig. 15. Constricted areas for backfill at a Minuteman facility

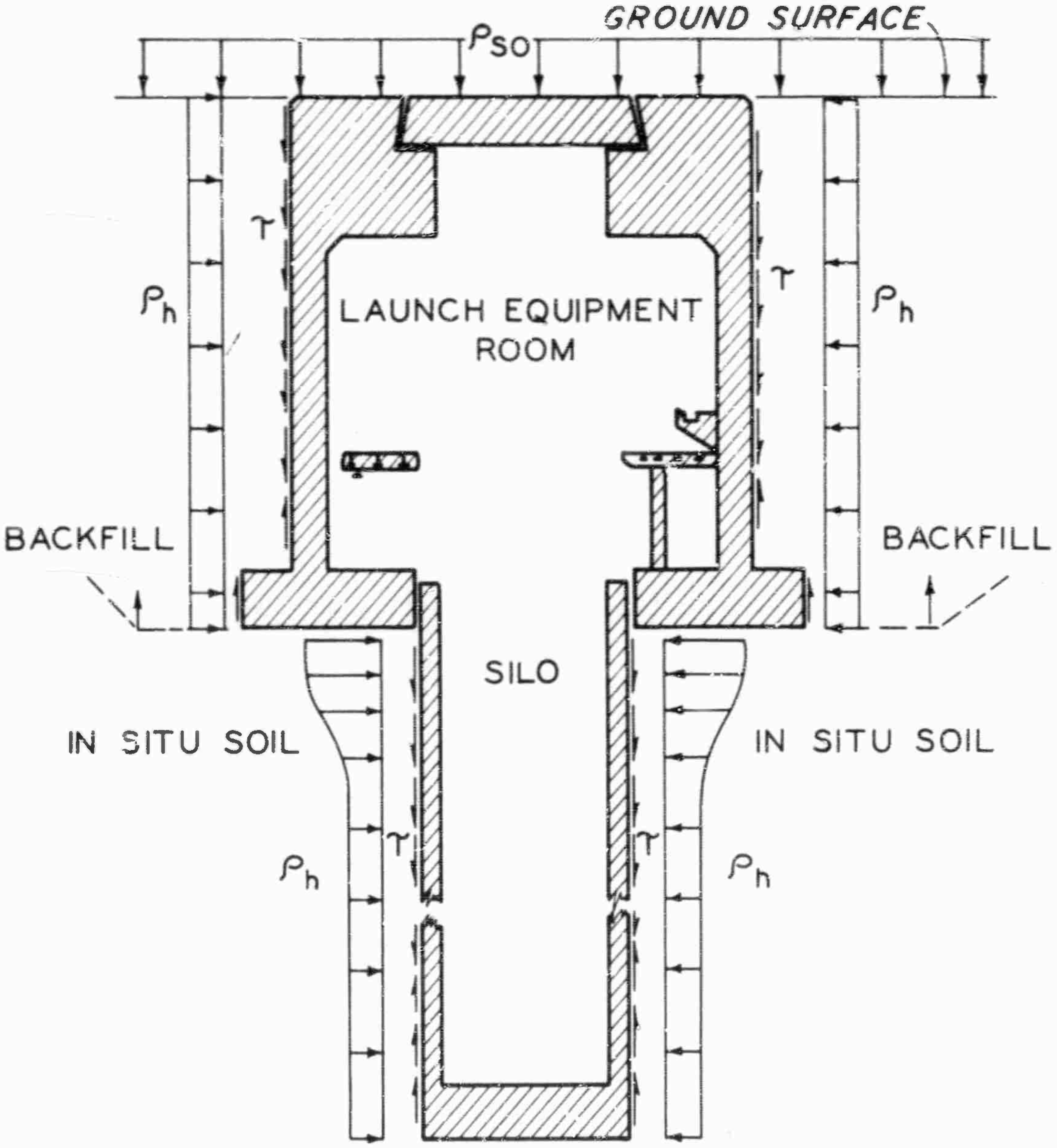

Fig. 16. Loading on a Minuteman launch equipment room and silo

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13. ABSTRACT

This paper describes the difficulties and problems in connection with design and construction of Intercontinental Ballistic Missile Bases. The problems arose primarily because of ~~(1)~~ the crash nature of the program, ~~(2)~~ the widespread extent areally of facilities in a given missile complex, which resulted in varied geological and water-table conditions, and ~~(3)~~ nonsite adaptation of general plans and specifications for a complex to individual facility sites in the complex. In spite of harassing design and construction problems which affected the timeliness and cost of construction, all missile complexes were successfully constructed, which involved 850 individual facilities.

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