Engineering Properties and Applications Of Nuclear Excavations

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The use of nuclear excavation for engineering projects depends not only on the size of the excavation but also on the properties of the material in and around the excavation. In a nuclear excavation several general zones are evident, including the true and apparent crater, crater fallback and lip throwout material, ground upheaval, and the rupture and plastic zones. The properties of the material in these zones are dependent on original medium characteristics and the effects of the detonation.

The hyperbolic shape of a crater lends itself to good slope stability. The problem of slope stability in soils or highly weathered rock will be more acute than in competent rock. The condition of the rupture zone, the amount of surcharge on the crater lip, and ground shock from later detonations impose additional problems to slope stability evaluation. The fallback material will obtain a certain amount of dynamic compaction as a result of the material falling from heights of several hundred feet. Further foundation stability, if necessary, can be accomplished by standard techniques.

Several applications of nuclear explosives in the highway engineering field appear feasible, including excavation of roadway cuts, aggregate production by open pit mining, drainage diversion or interception by craters, and landslide removal, encouragement, or stabilization. The feasibility of using large-yield explosions for engineering projects has been demonstrated in the U. S. S. R. During the last 20 yr, many large-yield conventional explosives have been used for excavation, mining, and dam construction.

•THE PLOWSHARE program was established in 1957 to investigate possible industrial applications of nuclear explosives. Among the many applications studied, large-scale excavation is one of the most promising. Up to the present time, nuclear excavation research has been primarily concerned with developing cratering parameters to a point where an excavation can be carried out with a reasonable degree of accuracy and safety. This technology has been sufficiently developed so that specific applications can be seriously investigated as to their engineering and economic feasibility.

The use of nuclear excavation techniques for engineering projects involves not only the size of the excavation but also the properties of the material in and around the excavation. These properties affect such problems as slope and foundation stability, drainage, and other related matters. The suitability of an excavation for engineering use will largely depend on the economic considerations associated with these problems. A thorough knowledge of the site conditions and the effect of the explosion on the medium is necessary to determine the applicability of nuclear excavation to any particular engineering project.

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TABLE 1

CRATERING EXPERIMENTS FROM WHICH INFORMATION ON ENGINEERING PROPERTIES HAS BEEN DERIVED

Name	Medium	Yield (kt)	Apparent Crater Parameters (ft)		
			Depth of Burst	Radius	Depth
NUCLEAR					
Jangle U	Alluvium	1.200	17	130	53
Teapot ESS	Alluvium	1.200	67	146	90
Neptune	Tuff	0.115	100	100	35
Danny Boy	Basalt	0.420	110	107	62
Sedan	Alluvium	100.000	635	600	320
HIGH EXPLOSIVE					
Scooter	Alluvium	0.500	125.0	155.0	75.0
Stagecoach No. 1	Alluvium	0.020	80.0	57.0	7.9
No. 2	Alluvium	0.020	17.1	50.5	23.6
No. 3	Alluvium	0.020	34.2	58.6	29.2
Buckboard No. 11	Basalt	0.020	25.5	44.7	24.9
No. 12	Basalt	0.020	42.7	57.0	34.7
No. 13	Basalt	0.020	58.8	36.8	16.2

A great deal of information is known about the phenomena associated with a cratering explosion (1). However, many uncertainties exist relating to the actual engineering properties of the various media which might be involved in a cratering detonation. This paper will discuss in some detail present knowledge in the following areas:

1. Engineering properties of craters produced by nuclear explosions.
2. Potential engineering applications of craters.
3. Soviet experience with the use of large-scale detonations for engineering applications.

ENGINEERING PROPERTIES OF NUCLEAR CRATERS

A nuclear crater consists of several general zones with different engineering properties. These are the true and apparent crater, crater fallback and lip throwout material, ground upheaval, and the rupture and plastic zones. The general composition and engineering properties of these zones are discussed. Knowledge of these properties is limited to investigations made on a few cratering experiments (Table 1). Figure 1, based on the Danny Boy event (2), shows a schematic cross section of a nuclear crater in a rock medium, indicating the zones of interest.

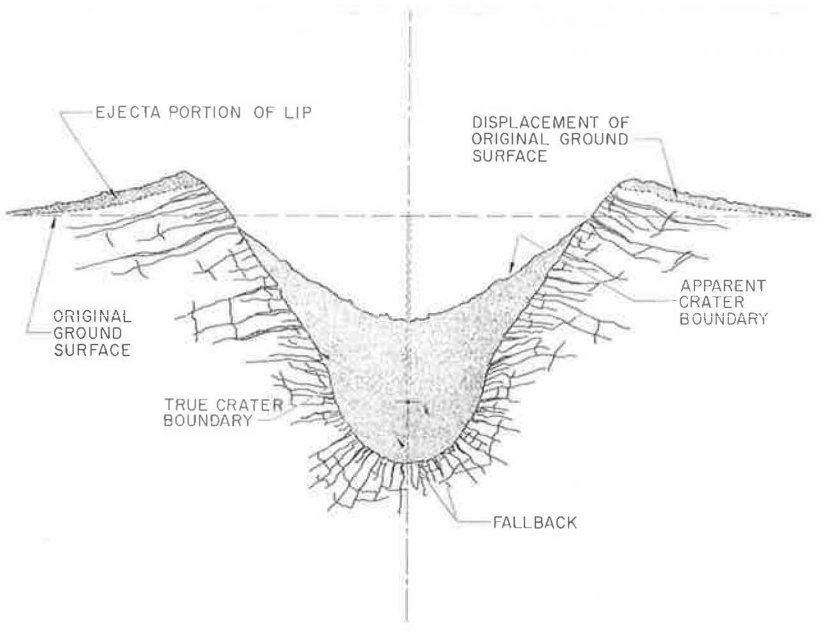

Figure 1. Schematic cross section of typical nuclear crater in rock medium, based on Danny Boy event.

Throwout and Fallback Material

Throwout and fallback material is that portion of the medium which has been put into trajectory and has fallen back into and around the crater. At the depth of burst at which maximum crater dimensions occur, about one half of the material is thrown out of the crater, whereas the remainder is fallback material. Ejecta is deposited on the lip of the crater out to a distance of about three crater radii. The fallback material is deposited in the true crater forming the apparent crater, whose shape is that of a hyperbola. Because throwout and fallback material are formed in the same way, their properties are similar. However, consideration should be given to whether the medium is relatively compressible, such as soil, or incompressible, such as rock.

Rock. —In a rock medium, the throwout and fallback material occupies a greater volume after the explosion than before the explosion. This swell is due to the increase in the voids when the natural jointing of the rock is disturbed. The rock size distribution, which affects the swell factor, is influenced by the medium, the depth of burst of the nuclear explosive, and, most importantly, the fracture pattern and soundness of the rock.

In a shallow detonation, much of the energy of the explosion is directed toward breaking up the overburden by a very strong rarefaction wave. In a deep detonation, the relatively weaker rarefaction wave breaks up less material. Thus, the ejecta and fallback material in a shallow detonation is broken at a much higher stress level, resulting in smaller particles and a low swell factor, but a deep detonation results in larger block sizes approximating the fracture pattern of the undisturbed material, producing a larger swell factor.

This phenomenon is seen in the three Buckboard cratering experiments. As the depth of burst was increased, block sizes increased. Studies are under way to better determine the rock size distribution and swell. Table 2 gives the results of a preliminary investigation based on volumetric differences from pre-shot and post-shot contour maps and estimated true crater and true lip volumes. The throwout and fallback material of the Danny Boy crater, at a scaled depth of burst of 142 $ft/W^{1/3.4}$, was determined to have a swell of about 25 percent, indicating that at the same scaled depths of burst, similar swell would be attained. With proper knowledge of the medium and careful selection of the cratering parameters, the rock size and swell factor may be somewhat controlled. The swell would also be expected to have an influence on the depth of the apparent crater. With several hundred feet of fallback material, a small change in the swell factor could affect the accurate prediction of the apparent crater depth.

Rock put into trajectory returns to the ground with great momentum. It exerts a large dynamic compaction effect on the material it hits. The compaction would eliminate weak points of contact and produce good interlocking and several points of contact between rocks (3). This tends to decrease the swell and produce a fairly stable mass. Rock flour produced by this compaction might contribute to instability; however, this would depend on the properties of the medium. Excessive rock flour has not been observed at the Danny Boy site but was observed at the Neptune crater.

Soil. —In a soil medium, the volume occupied by the ejecta and fallback material is less than the true crater volume. This difference in volume is caused by the compression and displacement effects from cavity expansion and the shock wave. An example of this shrinkage can be seen in the Sedan detonation. Based on pre-shot and post-shot contour maps, an over-all volume decrease of about 1.4 million cu yd of material was indicated. This represents about 10 percent of the true crater volume. A large amount of soil is vaporized and fused; however, compared to the total volume of material involved, this is considered insignificant. The engineering properties of the crater material, as a

TABLE 2

EFFECT OF SCALED DEPTH OF BURST ON PERCENT SWELL OF THROWOUT AND FALLBACK MATERIAL IN BUCKBOARD EXPERIMENTS

Buckboard Shot	Scaled Depth of Burst ($ft/W^{1/3.4}$)	Estimated Swell (%)
No. 11	81	10
No. 12	135	20
No. 13	186	50

whole, will not be affected by the fused material or the radioactivity resulting from the detonation.

The ejecta material, in the form of discrete masses of soil, can be observed in Figure 2. On impact, the mass distributes itself in the vicinity of the impact point. This is plainly observable in the many impact craters seen around the Sedan crater (4). The impact of this soil mass results in a great dynamic compaction on the surface material (4). Some material ejected from the Sedan detonation reached heights up to 2,000 ft. Thus, the material falling to the ground is successively compacted by subsequent falling material. A theoretical analysis of this dynamic compaction showed that soil dropped from heights of a few hundred feet would be compacted with a force greater than that of present mechanical compaction methods. Below the first few feet of material, high compaction has been observed in practice under field conditions (5).

Most throwout and fallback material in a crater formed in soil may be expected to be fairly well compacted and possess good density. Infiltration tests in the throwout material of the Sedan and Scooter craters indicated a decrease in the permeability of the material as compared to the pre-shot medium (6). Drill-hole data in the fallback material in the bottom of the Sedan crater indicate a density within 10 percent of the pre-shot density (7). Generally it may be concluded that most fallback and throwout material from a cratering detonation in soil will possess a density about the same as the pre-shot density of the material. These general conclusions must, of course, be evaluated with respect to a particular situation.

Lip, Rupture and Plastic Zones

The apparent lip of a crater is that material which surrounds the crater above the original ground surface. It is made up of the ground which has been upheaved by the explosion, the true lip, and the throwout material from the crater, the ejecta lip. The

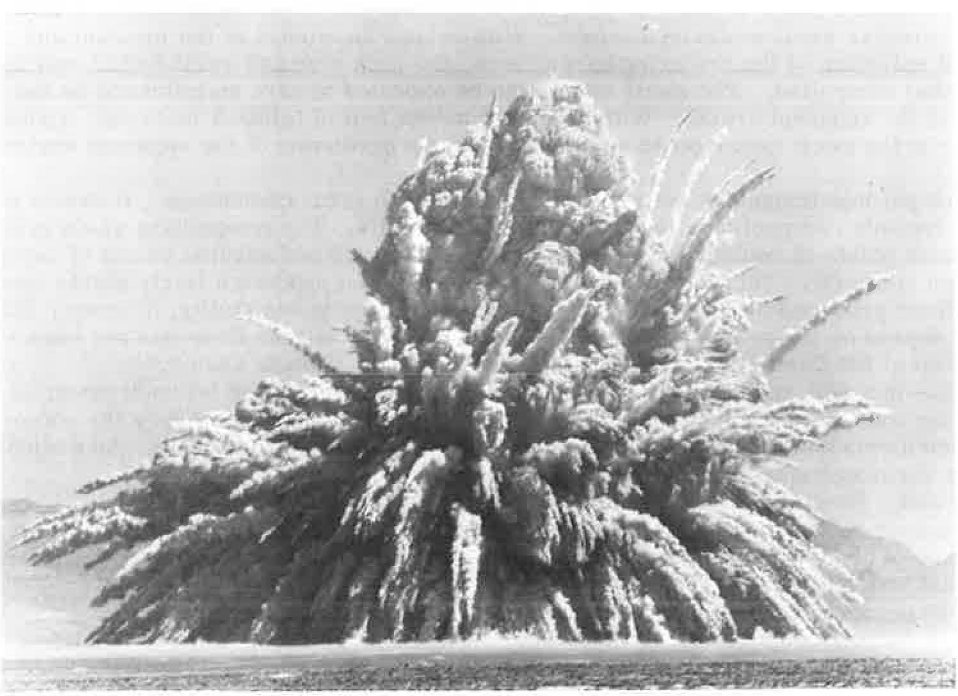

Figure 2. Sedan 100-kt detonation in alluvium, showing soil masses in trajectory up to heights of 2,000 ft.

amount of ground upheaval forming the true lip is related to the amount of distortion in the medium close to the detonation. This zone of material is called the rupture zone.

Rupture Zone and True Lip.—The surface of the rupture zone forms the true crater. In rock it is characterized by radial cracks around the cavity due to cavity expansion and horizontal cracks through the fracture pattern near the ground surface. The horizontal cracks are caused by surface spall and shear action along the true crater boundary. In soil, the rupture zone is significantly compressed around the shot point due to cavity expansion. Elsewhere, the medium is only slightly compressed by the shock wave action and the effects of cavity expansion.

These effects tend to cause an upheaval of the ground around the true crater. The Danny Boy crater had an average upheaval of 18 ft, with observed fracture pattern cracks opened as much as 12 in. (8). The Sedan crater upheaval averaged 10 ft (4). The true lip in rock is caused mainly by joint expansion, whereas in soil, displaced material from the cavity causes surface upthrust. Considering these mechanisms of formation, the true lip in a rock medium should be significantly higher than one in a soil medium.

The extent of the upheaval depends on the magnitude of the rupture zone. With an increase in the depth of burst a greater volume of the material is affected before the gases in the cavity escape to the surface, resulting in a larger rupture zone and greater upheaval. This is evident in the Buckboard experiments. As the depth of burst was increased, the height and radial extent of the lip upheaval zone increased. The upheaval around the Danny Boy crater extended out to a distance of 120 ft from the crest of the lip, a distance about equal to the radius of the crater (8).

Plastic Zone.—The rupture zone extends out to the plastic zone, where only small-scale shear failures and displacements are found. This is the transition zone between the rupture zone and the zone where the effects of the detonation on the medium have been insignificant. It is difficult to determine and has not been well investigated; however, it is felt that it exhibits no significant difference in physical properties from the original medium.

Throwout Lip.—The throwout lip is composed of the material ejected from the crater. This material falls on the upheaved true lip of the crater and out to a distance determined by the trajectories of the material. The amount of ejecta on the lip is dependent on the size of the excavation. Carlson (4) has developed a relationship between the mass of throwout material and the apparent crater volume for soil. The rock size distribution and the swell are important factors in determining throwout volume and lip height.

An interesting comparison can be made between the ejecta lips of Danny Boy and Scooter craters. The yields and depths of burst were similar; however, Danny Boy was a nuclear shot in basalt, whereas Scooter was a chemical high-explosive shot in alluvium (Table 1). The Scooter detonation was influenced by a secondary gas acceleration caused by the relatively high moisture content of the alluvium (10 to 20 percent) and the use of a chemical explosive. These factors generate a large amount of gas in the vicinity of the detonation point. This produces a sustained thrust which imparts a greater velocity and trajectory to the throwout material. Thus, the apparent crater volume of Scooter was 2.5 times that of Danny Boy. The Scooter ejecta lip had a maximum thickness of 5 ft and extended more than 400 ft from the edge of the crater. The Danny Boy maximum ejecta lip thickness was 10 ft and extended about 200 ft. Therefore, besides the differences in the medium, factors such as moisture content and type of explosive must be considered for the accurate prediction of ejecta lip parameters.

Apparent Lip.—The combination of the true and throwout lips makes up the apparent lip of the crater. Observations of many craters indicate that the lip crest occurs at about 1.2 apparent crater radii. The height of the apparent lip crest has been related to the radius of the apparent crater (4). Based on comparison of pre-shot and post-shot contour maps of the Buckboard series, the volume of the apparent lip was observed to increase with increasing depth of burst.

Apparent lip heights are not symmetrical; wide variations are evident in each crater. For example, the Sedan crater apparent lip ranged from 20 to 100 ft. This

variation is probably related to unsymmetric gas venting from the cavity through weak zones in the overburden.

Lip heights in a row-cratering shot are much higher than for a single crater because in row cratering, the throwout and upheaval are confined to a much smaller perimeter. Recent high-explosive row shots in alluvium have shown lip heights to be about twice as high as the lips from a single crater (9).

Slope Stability

The most critical area of concern in the engineering use of a nuclear excavation is that of slope stability. In this respect, it should be kept in mind that standard methods of slope stability analysis are as important in nuclear excavations as in conventional excavations. Problems relating to foliation, groundwater, etc., must be thoroughly evaluated before nuclear excavation is considered. Due to the great depths of excavation economically feasible with nuclear explosives, a proper stability analysis becomes even more important (10).

Fallback Slope.—The fallback slope is similar to a talus slope, composed of broken material and concave upward with the flattest portion near the base (Fig. 1). The steepest part of the fallback slope is usually less than the angle of repose of the material. The material is thinnest where the slope is steepest. In effect, the head of the slope has little overburden and the toe of the slope is reinforced. This lends itself to good slope stability.

One obvious problem with the fallback slope is that of rockfall or erosion. Rockfall generally is of a minor nature. Large overhanging boulders and unstable sections could be scaled before the excavation is put to engineering use. The slopes are such that rocks would not tend to fall of their own accord. However, provisions should be made for adequate rockfall control, if necessary.

Erosion and mudslides might present problems in an excavation in fine-grained material. This depends on the medium, and should be thoroughly investigated. Although in an arid climate, the slopes of the Sedan and Danny Boy craters have been essentially stable since their formation in 1962.

Rupture Zone Slope.—The surface of the rupture zone generally forms the top of the apparent crater and extends downward along the true crater surface (Fig. 1). The slope of the true crater must be considered for stability of the entire excavation. The detonation would probably weaken the stability of the slope as compared to its preshot condition and, therefore, warrants special consideration.

The fractures induced in a rock rupture zone tend to slope back from the excavation. This is due to horizontal spall fractures uplifted close to the excavation. There are no major changes in the orientation of the material, and good interlocking remains. Also, the fallback material presents a large resisting force at the toe of the rupture zone. Thus, in rock, these factors should contribute to a stable slope condition. However, adverse conditions such as faults, dips, and strikes should be investigated.

A soil rupture zone slope is compressed at the base by cavity expansion and somewhat densified elsewhere due to shock wave effects. This, as well as the resisting force of the fallback material at the toe, contributes to slope stability. However, many more problems may be present to disturb the stability of soil rupture zones. For example, in some media the effect of the detonation might cause spontaneous liquefaction of the rupture zone material. The sudden removal of material during excavation could induce lateral forces from expansive properties of the rupture zone, resulting in slope failure. Slope stability conditions in soil excavations greater than a few hundred feet are relatively unknown. A great deal of knowledge must be gained before a proper evaluation of slope stability in a nuclear excavation in soil can be made.

Lip Surcharge.—A major problem relating to slope stability is the effect of the lip surcharge around the crater. This overburden adds greatly to slope instability. The lip surcharge rests on the rupture zone. Several hundred feet of lip overburden in a large excavation could, in itself, cause failure of the slope. The problem is more critical in soil than in rock. Removal of this lip material is possible but would, in all probability, be economically prohibitive. This problem becomes much more critical in row-cratering shots where the lips are higher than single shots.

Other Slope Stability Considerations. —If an excavation is to be accomplished by more than one detonation, the problem of what will happen to the slopes of a previously excavated channel exists. The shock wave from a detonation in close proximity to the excavation, in a direction longitudinal to the excavated channel, may induce large-scale slope failures.

One solution to this and other problems of definite slope instability is the intentional overexcavation of the original channel. Subsequent slides, either natural or induced, would fill up the channel to about the required depth.

Foundation Stability

If the excavation is to be used as a roadway, the question of foundation stability becomes an important factor in design. The bottom of the apparent crater consists of several hundred feet of fallback material. Earlier in this report it was pointed out that fine-grained fallback material should attain a density similar to pre-shot conditions, whereas competent rock should be well compacted, with several points of contact. Tests must be conducted to ascertain the actual bearing capacity of the foundation. In many cases, excess moisture, poor density, excessive fines, etc., require correction by standard engineering methods before a proper subgrade is obtained.

Additional settlement, if required, can be accomplished by such methods as surcharge and mechanical compaction. Fines between rocks may be washed out by water sluicing. The foundation may also be considered a subgrade with a low bearing capacity. Therefore, a properly designed flexible pavement would eliminate many problems of foundation instability. The fallback material is of a more or less homogeneous nature. Therefore, uniform settlement is expected. Differential settlement is measured and corrected, if necessary.

Summary of Engineering Properties

A rock medium is much better suited to nuclear excavation techniques than soil because of the greater stability problems encountered in a soil excavation. However, the greatest economic benefit from nuclear excavation methods is realized in rock. Each site must be individually investigated with regard to its proposed use and its properties after completion of the excavation.

Engineering properties depend on the medium, depth of burst, and yield of the explosive. Proper evaluation of these parameters yields the most economical set of conditions for the type of excavation under consideration. Thus, in the design of a nuclear excavation, the engineer must be fully aware of the effects of these parameters in order to properly evaluate the use of nuclear explosives for large-scale excavation.

APPLICATIONS OF NUCLEAR EXCAVATION

With a thorough knowledge of the technology and resulting properties of nuclear excavations, many applications become much better defined. This section is designed to introduce some of the applications related to the highway engineering field, and to stimulate thought on other possible uses. Applications concerned with roadway excavation, drainage, aggregate production, and landslide prevention and correction are discussed. It is emphasized that employment of nuclear explosives should be limited to situations where conditions allow their use. As with any general discussion of engineering methods, circumstances may exist that would prevent their use, but this should not eliminate consideration of these applications. Even if conditions rarely permit the feasibility of a project, the techniques should be well developed and readily accessible for use. The economics of these applications differ from one case to another; however, it is felt that with the proper set of conditions, nuclear techniques provide the most economic and realistic solution to many engineering problems, as well as reducing construction schedules by several seasons or years in many cases.

Roadway Excavation

The most obvious application of nuclear excavation is in the excavation of a deep cut for use as a roadway (Fig. 3). Unlike a channel excavated for a waterway, a

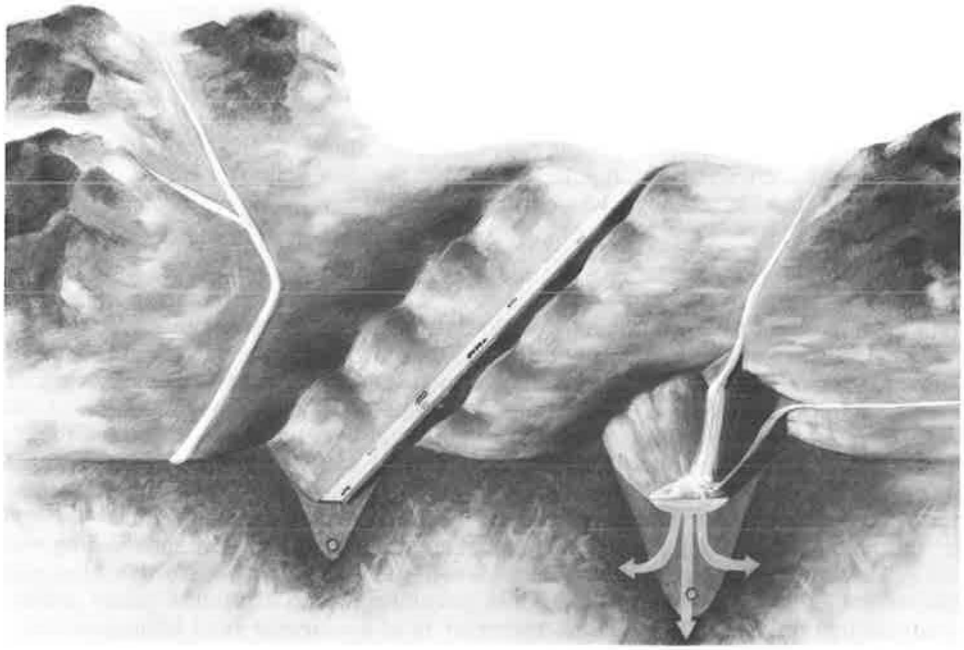

Figure 3. Potential applications of nuclear explosives in roadway excavation and drainage diversion and interception.

roadway must have a smooth bottom, close to the final design parameters. Otherwise, excessive, perhaps prohibitive, amounts of cut or fill are required to bring the roadway to the proper grade. Also the total roadway width must be such that it will fit into the bottom of the channel with adequate space for drainage and rockfall zones.

Present cratering technology indicates that the size of the excavation can be controlled by varying the yield and depth of burst. By varying depth of burst, a single yield can excavate a wide range of depths. Thus, with a relatively few standard-yield explosives, it is possible to design the excavation so that a smooth channel with approximately the desired depth is formed.

The standard use of nuclear excavation technology would lead to a re-evaluation of present highway design methods. In many cases, terrain need not be the dominating factor in determining highway routes. Studies, such as Carryall (11), illustrate that there are situations where it is more economical to design a highway through terrain requiring deep nuclear excavations than through terrain with shallower conventional excavations. Routes normally considered economically prohibitive could be undertaken. For example, Highway 40 through Nevada circumvents several mountain ranges between Lovelock and Battle Mountain, a present road distance of about 125 mi. Two 600-ft road cuts through these ranges would reduce this road distance by about 35 mi. The Southern Pacific Railway would save about 50 mi between these points. Road-user benefits by such reductions in road mileage cannot be lightly overlooked. If safety conditions such as ground shock will not allow complete excavation of a cut, it may be feasible to partially excavate the cut by nuclear explosives, conventionally excavating the fallback and rupture zone material to produce the required excavation.

One of the deepest highway excavations was at Carquinez, Calif., in 1958 (12). The maximum depth of cut was 300 ft with a volume of 8.8 million cu yd of bedded shales and sandstones, costing $0.35/cu yd for excavation and overhaul. If safety conditions permitted, a 100-kt detonation, similar to Sedan, would have excavated over 6 million cu yd of this material at less than half the conventional cost. A 50-kt detonation could have excavated almost 4 million cu yd at about two thirds of the conventional cost.

The remaining required excavation would be either in fallback or rupture zone material. Thus, conventional excavation costs would also be reduced. These comparisons are based on a total cost of $1 million for the nuclear excavation in both cases (13). In this particular case, of course, the population density in the area did not permit the use of nuclear explosives.

Drainage and Diversion and Interception

Drainage, one of the greatest concerns to the highway engineer, is a problem for which nuclear excavation techniques can provide a number of solutions. Roadway excavation with nuclear explosives will produce certain drainage benefits. In rock, the fallback material in the channel has sufficient porosity to accept all rainfall in the channel, allowing this runoff to percolate down to the bottom of the true crater and dissipate into underground permeable layers. The upheaved lip prevents runoff from entering the channel (Fig. 3) and actually diverts such runoff to lower ground for disposal. These solutions should be undertaken only when permitted by conditions considering stability and settlement.

In many situations, large drainage structures must be constructed to provide for seasonal floods or exceptional flows. The excavation of a large crater to intercept most or all flow reduces or eliminates drainage structure requirements. The water in the crater, which might otherwise be wasted, could serve useful purposes such as groundwater recharge or a water supply. The Sedan crater has a capacity of 3,000 acre-ft in surface storage and 30 percent more in subsurface storage. A crater can be produced to meet required size specifications of flood conditions up to certain limits, dictated by safety factors. A trench cut through the upheaved lip provides an access for water as in Project Carryall (11). This method is also applicable in intercepting mudslides or earth flows.

Aggregate Production

The increased requirement for road and highway construction is resulting in rapid depletion of present sources of aggregate in many locations. Low-grade aggregate and stabilization methods are being used in increasing amounts to avoid uneconomical

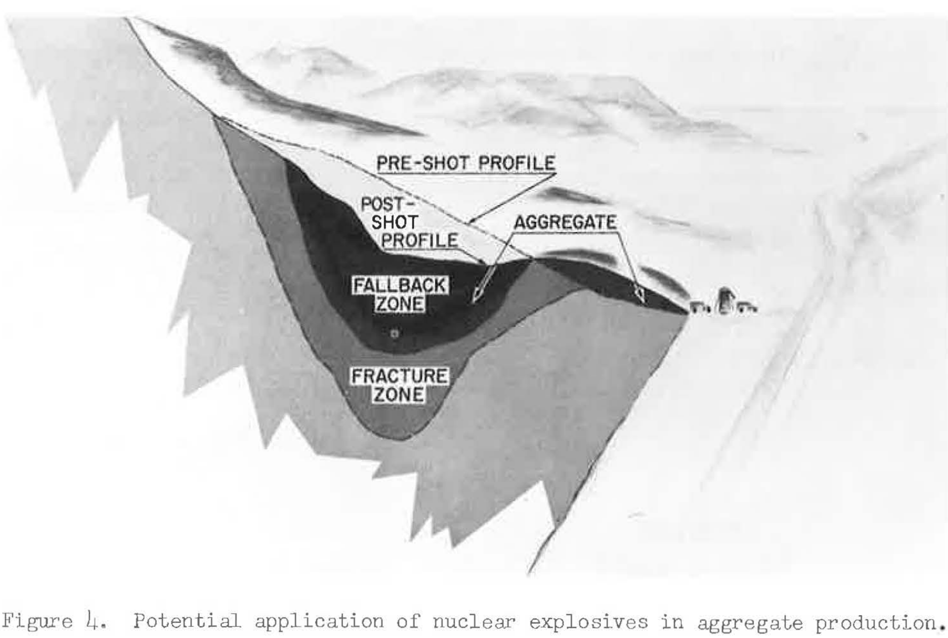

Figure 4. Potential application of nuclear explosives in aggregate production.

quarrying or long haulage. Nuclear explosives provide a method for economically breaking up a large amount of rock for use as aggregate. If the fracture pattern of the rock is sufficiently small so that secondary blasting would be minimum, a very deeply buried explosive provides the greatest amount of broken material. Otherwise a shallower detonation is required to produce smaller breakage by the action of the stronger rarefaction wave.

Access to such a quarry on level ground is difficult because of the steep sides of the crater. A quarry on the side of a hill or mountain is more feasible. The resulting crater is asymmetrical as shown in Figure 4, a scaled-up version of the Neptune crater. On a steep slope, much of the material rolls downhill with more subsequent internal grinding, producing smaller rock sizes. Neptune was detonated on a 30° slope and material amounting to about half of the volume of the apparent crater was ejected downhill (14). The "principle of directed throwout" (5) can be used to throw virtually all broken material downhill.

The uphill rupture zone slope is very steep and unstable. Most of this portion of the rupture zone would very likely collapse into the crater, providing significantly more broken material. The fractured material in the remaining portion of the rupture zone also provides a source of easily obtainable aggregate. If the detonation in Figure 4 were 100 kt, about 15 million cu yd of material would be broken up. Of this volume, about 5 million cu yd would roll downhill. The collapse of the uphill rupture zone would produce an additional 5 million cu yd and at least 15 million cu yd would also be present in the remaining portion of the rupture zone. Thus, this detonation would provide a total of 35 million cu yd of potential aggregate.

In some cases an excavation weakens a slope sufficiently to cause a major landslide to occur. This could involve a volume of material many times over the volume of the initial excavation. The Madison Canyon slide in Montana in 1959 had a volume of 43 million cu yd (15). This material was initially held in place by a buttress of outcropping quartzite and dolomite, which was buckled by an earthquake. This entire mass could have been brought down at any previous time with a properly placed small nuclear explosive. In a similar situation, large quantities of aggregate or fill material may be deposited at the base of a hill, ideally located for access and utilization.

These applications of aggregate production are also useful in the field of open-pit mining. The material which is normally ejected from the crater comes mainly from the upper portion of the medium, whereas the fallback material is from the lower levels. Thus, it is possible to remove overburden from an ore-bearing body and, at the same time, break up a large portion of the ore without excessive dilution. This same principle could be applied to aggregate production for removing overburden deposits and exposing and breaking up good quality aggregate.

Landslide Prevention and Correction

As a result of the great increases of traffic volume in recent years, requirements for shorter routes, wider pavements, and improved grades have become necessary.

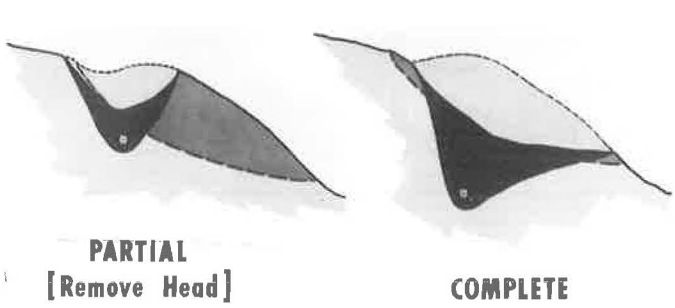

Figure 5. Use of nuclear explosives in potential landslide excavation.

The engineer is faced with deeper cuts, higher fills, and alignments which must overcome rather than avoid obstacles. Thus, the number and size of potential landslides are greatly increasing. Present solutions sometimes require exorbitant costs. For example, the filling of the reservoir behind Grand Coulee Dam by landslides has cost at least $20 million in the past 20 yr in avoidance and correction of damage. The railroad systems in the United States and Canada spend over $5 million a year on landslide prevention and correction and many State highway departments spend up to $1 million a year (16). Nuclear explosive techniques can help to reduce the cost of such solutions in the future. With the proper use of nuclear explosives, it appears possible to excavate, induce, or stabilize landslides. The relatively short time in which a device can be placed and detonated in an emergency could eliminate dangerous situations relating to landslides.

Landslide Excavation.—At the present time, potential landslide excavation is considered economical for volumes between 20,000 and 2,000,000 cu yd (16). The volume which can be excavated by nuclear explosives is determined only by safety limits in the vicinity. Thus, a potential landslide may be totally or partially excavated (Fig. 5). In a total excavation the detonation can be designed so that the apparent crater closely conforms to the slip plane of the landslide. In a partial excavation the head of the landslide is excavated, reducing the driving force of the landslide. By directed explosions (5), this material can be placed at the toe of the potential landslide for added stability. The crater also provides a method of drainage diversion under the slip plane of the landslide.

The Pacheco Pass Highway in California serves as an example of how this method may be used in highway construction. A 280-ft highway fill is being constructed in a canyon to avoid a potential landslide (Fig. 6). The volume of the fill will be 2.2 million

Figure 6. Pacheco Pass Highway in California with locations of 280-ft highway fill and slide area indicated. (Courtesy of the California Division of Highways)

Figure 7. Air view of Madison Canyon slide somewhat east of drowned toe of slide.

Figure 8. Use of nuclear explosives in potential landslide inducement by toe removal or overcoming static friction.

cu yd; the cost is estimated at about $1.5 million (17). However, the landslide danger still exists because failure will adversely affect the fill (18). A 100-kt detonation can excavate most of the slide and deposit the material into the location for the fill. The resulting crater should have sufficient volume to intercept any additional slides which might occur on the hillside opposite the fill. The canyon now has little water capacity; the crater will greatly increase this capacity and reduce the present necessity for a 9-ft concrete-arch culvert through the fill. Thus, use of a nuclear detonation will eliminate the landslide danger, reduce drainage requirements, and place the major portion of the required fill.

Nuclear explosives may also be used to excavate immediately a landslide which has blocked a valley stream or presents a generally dangerous situation. The Madison Canyon landslide blocked the valley to heights of from 200 to 400 ft (Fig. 7). Water, backing up behind the natural dam, would undoubtedly have eventually destroyed the landslide. The resultant flood would have been devastating. The Corps of Engineers spent 2 mo at a cost of $1,715,000 to develop the landslide into an earth dam. This earthwork was quite difficult and dangerous (15). A 50-kt explosive could have been placed and detonated within 10 to 20 days to completely breach the slide. If a 10-kt explosive were used, the crater produced would have disrupted the landslide enough to prevent a dangerous accumulation of water. Besides the beneficial emergency use, the economics of this application is obvious.

Landslide Inducement.—Nuclear explosives can also be used to trigger an incipient landslide in several ways, such as toe removal, overcoming static friction, or simple spalling of the complete landslide (Fig. 8). When the toe is excavated, a large resisting force is eliminated. This, essentially, was the situation at Madison Canyon. Proper knowledge of the potential slide allows an excavation sufficient to cause failure of the slide. The explosive may be placed to produce a crater within the landslide itself. The shock wave and the resulting shear forces tend to overcome the static friction forces on the slip plane and produce additional driving force on the slide area. In many cases, this is sufficient to induce slide failure.

Landslide Stabilization.—Another possible application relating to landslides is that of stabilization by a subsidence crater. A deeply buried explosive produces only a cylinder of material, collapsed into the cavity produced by the detonation, causing a subsidence on the surface (Fig. 9). This method has several advantages:

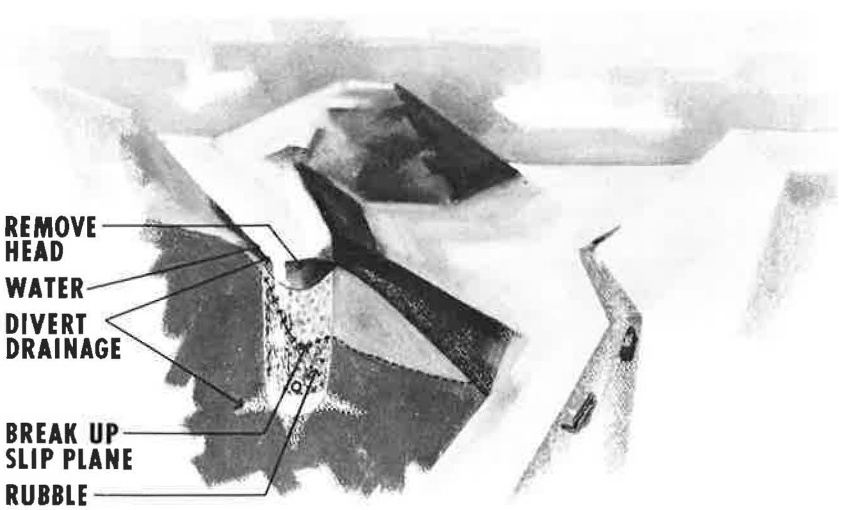

Figure 9. Potential application of nuclear explosives in landslide stabilization by use of subsidence crater.

1. The subsidence partially removes the head of the landslide, thus reducing the driving force in the potential landslide;
2. The slip plane is effectively broken up in the chimney area, which helps to stabilize the slip surface of the potential landslide;
3. Drainage is diverted from the slip plane to an area well below the potential landslide mass;
4. This method requires a very low-yield nuclear explosive, thus problems of inducing a landslide or affecting nearby structures are minimized; and
5. The detonation is almost completely contained and, therefore, the radioactivity escape is very small.

These various applications of dealing with landslides involve many problems that should be carefully considered before such a method is undertaken. However, it is felt that a careful investigation of the factors concerned will lead to many situations where one of these solutions would be feasible.

Summary of Engineering Applications

The possible applications of nuclear explosives in the highway engineering field require much further investigation before being undertaken. It is hoped that these suggestions will motivate the engineering community to their further evaluation and stimulate thought for other possible applications in the engineering field. Because of the economic and time savings possible on many projects through the use of nuclear explosives, engineers should be aware of the possibilities of this method.

SOVIET USE OF LARGE-SCALE EXPLOSIVES

Explosions in the kiloton range have been used for many years in the U.S.S.R. in the fields of mining, excavation, and dam construction:

> By explosion it is possible to excavate almost instantaneously tremendous masses of ground and obtain cuts for laying of roads or foundations ... to deepen and widen rivers and water reservoirs... to construct dams by hurling ground into river beds in such a way that this ground formed a dam of definite previously prescribed form (19).

Soviet scientists during the past few years have conducted a major program of research to develop scaling data, basic phenomenology, and operational experience in the use of chemical explosions for engineering purposes (20). Projects have been executed with great economic and engineering success. Applications on a much larger scale are planned for the immediate future.

In addition to basic research in explosion and cratering phenomena, the Soviet Union has developed the "principle of directed explosions" into an engineering tool. When a charge is detonated in the vicinity of a cavity, either on or below the surface, much of this explosive energy is directed toward the cavity (Fig. 10). The dashed line indicates surface motion from a horizontal surface. The solid line illustrates ground motion from a detonation in the vicinity of a cavity. Thus, it can be seen that the energy from a detonation is concentrated in a specific direction. If the cavity is in the form of a surface "concavity," either natural or artificially produced, this method can be used to direct throwout of material for deposition into a predetermined location. Subsurface cavities can be used to produce greater breakage, increase the volume of excavation, compact unstable soils, or remove them from below fills (21).

Using directed explosions on an incline, the main fill portion of an earth- or rock-fill dam may be placed, making use of a natural concavity (such as the bend of a river) or one produced by preliminary explosions. In seven throwout dams, about 60 percent of the throwout material fell within the prescribed limits of each dam (5).

It appears that this mass of throwout material does not conform to required construction specifications. However, according to Soviet technology,

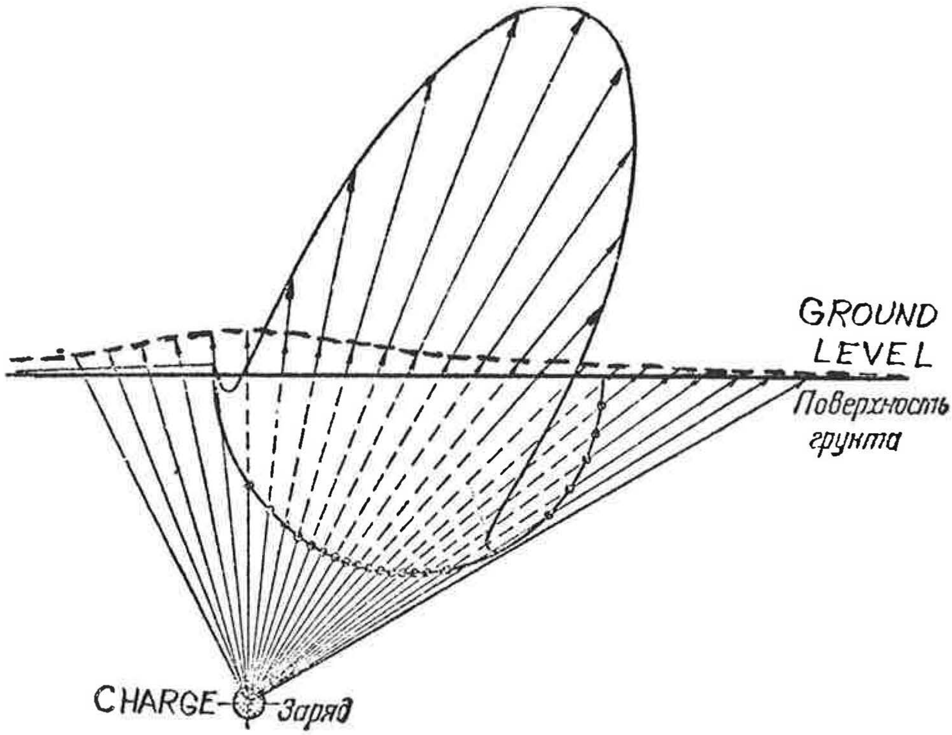

Figure 10. "Principle of directed explosions" as developed by U.S.S.R.

> Ordinarily the throwout material ... appears to be unsuitable as a solid mass for a structure which depends on the strength of the earth fill. This impression, however, is incorrect because it pertains to the surface layers of the throwout. If attention is directed to the deeper portions of the mass of material thrown out by the explosion, the impression is changed. Studies carried out in pits and bore holes indicate that the internal portions of the mass of throwout, as a rule, possess sufficient compaction and strength (5).

These applications and observations have apparently been borne out in practice. One of the best examples of the directed throwout method was in the construction of the Government Electric Station No. 1 Dam in 1943 (5). Although this was a relatively low dam (28 m), much information is known about it, and the engineering use of large explosives is well illustrated.

The original plan called for the conventional construction of two cofferdams and a diversion pipe to divert the water from the dam site. However, because construction was necessary in a low water cycle, postponement for an entire construction season would have been necessary. Therefore, it was decided to construct the cofferdams by directed explosions.

The project plan for the explosion method is shown in Fig. 11. First, a cofferdam on Channel A was constructed; this was designed to stop the flow in Channel A and reduce the flow in Channel C for 15 min. The upstream cofferdam was constructed 3 min after this, followed 3 sec later by the downstream cofferdam. Concavities were created in the right banks of the two main cofferdam explosions by auxiliary explosions, detonated 4 sec before the main charge. The parameters of the explosions and cofferdams are given in Table 3.

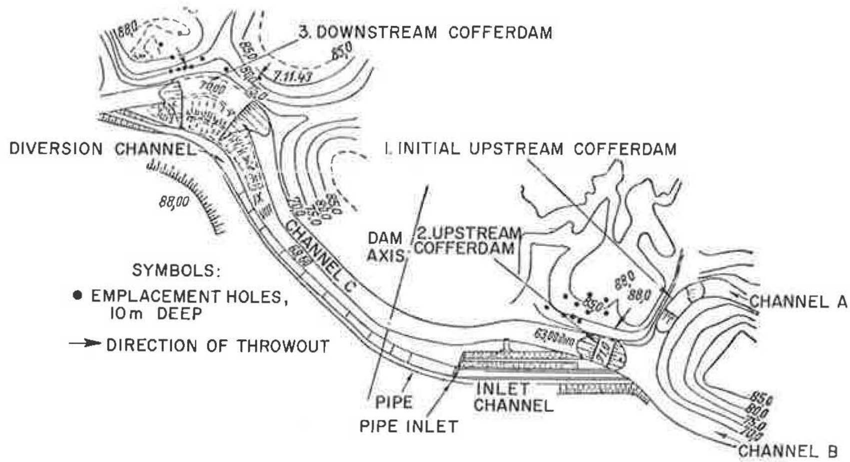

Figure 11. Project plan for construction of Government Electric Station No. 1 Dam; numbers indicating sequence of cofferdam construction by directed throwout; elevation contours in meters.

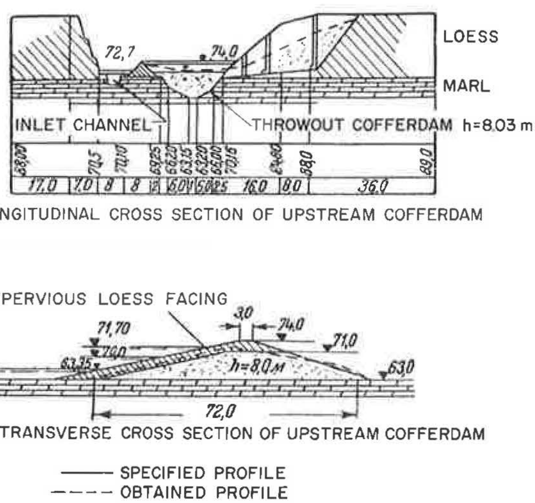

Figure 12. Longitudinal and transverse cross sections of upstream cofferdam during construction of Government Electric Station No. 1 Dam, showing pre-shot and post-shot profiles.

TABLE 3

COFFERDAM PARAMETERS FOR THE GES NO. 1 DAM

Cofferdam	Total Charge Wt (kg)	Cofferdam Ht (m)	Cofferdam Vol (cu m)
Initial	1,000	4.5	2,250
Upstream	11,500	8.0	5,000
Downstream	15,500	12.0	7,700

The resulting profiles of the cofferdams closely approximated the specifications. The longitudinal and transverse cross sections of the upstream cofferdam are shown in Figure 12. The simultaneous construction of the two cofferdams effectively diverted the water; no seepage was observed. The explosion plans were formulated in 5 days; emplacement took 4 days, and the

detonation took 1 day. Thus, the cofferdams were placed and the diversion was accomplished 10 days after it was decided to construct them with explosives. This method shortened the construction period by 3 mo and saved an estimated 1 million rubles. Manpower requirements were reduced from 45,000 to 610 man-days. During construction of the main dam, 78,400 kg of explosives were detonated to direct 30,000 cu m of material into the front part of the dam spillway. In the similar construction of the cofferdams for the GES No. 3 Dam (5), settling of about 3.5 percent became stabilized within a year. No fissures or seepage were observed, and the cofferdams exceeded expectations.

This method of dam construction has been used to a certain extent in the United States. During the construction of Cabinet Gorge Dam (22), the Clark Fork River was diverted into tunnels by a cofferdam built by the displacement of 60,000 cu yd of rock from a 200-ft cliff by a 65,000-lb dynamite detonation. However, engineers in the United States generally have not practiced this method because of the general feeling that the material requires rehandling and grading to obtain a stable mass (23).

In December 1960, explosives were used in the Soviet Union to excavate a cut 500 m long for use as a railroad. A total volume of 250,000 cu m of rock was excavated. Within 4 mo after the detonation, train service on the line was opened (24). During construction of a railroad in China, a canal was excavated to cut off a meander to divert a river. Following the diversion, directed explosions were used to produce fills in the river bed for the railroad construction across the meander (19).

The largest explosions thus far reported by the Soviets have been in the mining field. Although numerous projects have been reported, the most significant one was in China in 1956. Three detonations were used to remove overburden and break up a copper ore deposit at the Bayinchansk Mine. In July, a 1.64-kt charge was detonated, followed by a 4.78-kt explosion in November. On 31 December 1956, a 9.2-kt detonation excavated 2 million cu m of overburden and crushed 7 million cu m of copper ore. This charge was buried at a depth of 60 m, producing a crater 100 m deep and 500 m in diameter (19).

The foregoing applications are but a few representative examples of the type of work with large-scale explosives accomplished in the Soviet Union. The success of this program is evidenced by the larger scale future projects that are planned. In Alma Ata a dam almost 300 ft high with a volume of 5 million cu m will be constructed by an 8.4-kt detonation. This dam is planned to stop mudslides which periodically threaten the communities in the valley (25). A 16-kt detonation is planned to excavate 5 million cu m for a road cut in the Ala-Tau Mountains (26). In Yakut two 40-kt explosions will displace 10 million cu m of earth to strip a coal layer for development (27). This project would require 8 yr by conventional mining techniques, whereas with these two detonations the time will be reduced to 2 yr. On the Angora River a 30-kt explosion is planned to excavate a 7-km channel through the Shaman-Kamen Rock (28).

All Soviet projects thus far have been conducted with chemical explosives. Published reports have indicated that future projects will also use only conventional explosives. It is not known if research is being conducted into the possible use of nuclear explosives for engineering purposes. However, the Soviets know of the great economic advantage of nuclear explosives and that radioactivity can be adequately controlled (29). The yields of the explosives for these projects are definitely in the range where nuclear explosives would be economically justified. For example, in a 40-kt detonation, conventional explosives would cost about $0.05/lb of explosive energy and would require an underground chamber with a volume of about 45,000 cu m. A 40-kt nuclear explosive would cost $0.0125/lb of explosive energy (assuming $1 million cost) and require a 30-in. hole down to the desired depth of burst. It would be reasonable to assume that serious consideration is being given to the future use of nuclear explosives.

Unfortunately, the Soviets have not published the experimental arrangements and results of their research and operations in sufficient detail to permit the incorporation of their work in our analysis. It is hoped that these data will be made available in the near future for evaluation and subsequent research. On the basis of available information, we are studying phenomena such as directed throwout and dam construction with explosives.

In summary, the use of large-scale explosives for engineering purposes has generally been proven technically and economically feasible by the U.S.S.R. Their work has been summed up by Professor Pokrovskii (19):

> In the field of study of explosion and its practical application, Soviet scientists have attained great success. There is no doubt that in the future, too, our science of explosion and of explosion technology will reach even greater progress.

CONCLUSIONS

A thorough knowledge of crater formation and the resulting properties of the medium is necessary before a realistic evaluation of an engineering application of nuclear explosives can be made. A number of areas in the highway engineering field are open to nuclear techniques, particularly in the fields of excavation, drainage, aggregate production, and landslide correction. Any possible application would require extensive study before a project could be undertaken. The success in the Soviet Union demonstrates the technical and economic feasibility of using large-scale explosions for practical engineering applications. Recent Plowshare developments have shown that nuclear explosives can be used for such projects with safety.

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