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Paper

INVESTIGATION OF GRANITE BORING USING HIGH SPEED LIQUID PROJECTILES

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ABSTRACT

An experimental study of granite boring by high speed water projectiles (impulsive jets) was carried out. The projectiles used as a boring tool were generated by a launcher where the chemical energy of a gunpowder was converted into the kinetic energy of a projectile. Various patterns of the distribution of sites of the projectiles impact on the samples surfaces were examined. As a result of the study process feasibility has been estimated.

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1. INTRODUCTION

Application of high energy water streams for fracturing brittle materials in mining and construction was studied in a number of works [1-7, etc]. The previous studies [8-14] indicated that the high speed projectiles have a potential of becoming a tool for boring brittle materials, e.g. a rock layer. The development of a launcher for generation of these projectiles constitutes a mission of the proposed study. The immediate objective of this study was to estimate the energy required for granite crashing and to evaluate the effectiveness of the use of the launchers as a part of a rock boring system.

Bench scale launcher prototypes and setups for fastening the launchers and granite targets were designed and constructed. While the design of the launcher used for the performed experiments was determined by the available resources rather than by the optimization conditions, the boring of granite was successfully attained. A sequence of the projectiles impacting a granite target crashed it and converted into rubble which then can be removed by the water stream from the impact zone. This will assure the advance of a boring head and its penetration through a layer of a brittle material.

The projectiles were generated by powder combustion which expels a water load through a nozzle. The pressure of the combustion products and the geometry of the launcher assured desired acceleration of the projectile. The material fracturing by the projectile depends on the stress waves generated in the target as well as on the change of the properties of the target material due to high hydrostatic pressure developed in the impact zone. Both, the stress waves and hydrostatic pressure are determined by the momentum density that is projectile velocity and cross section area. This study, however, was carried out at a nozzle exit diameter of 2 mm. Thus the variation of the area of impact was limited and the impact conditions were practically determined by the projectile momentum. At this study water was used as a working fluid and a commercially available gunpowder provided the necessary energy.

While the exit nozzle diameter in all performed experiments was constant, the process variables included the mass of water (working fluid) and powder (energetic fluid), standoff distance, target material and, finally, the distribution of a multiple impacts on the target surface. The amount of the energy used was estimated by the heating value of the powder charge. High speed filming was employed to estimate the variation of the projectiles velocity between the nozzle exit and the target surface. Because no comprehensive parametric study of the process was carried out, the determined energy and media consumptions constitute a lower estimate of the process requirements.

Previously a number of experiments involving concrete demolition, metal piercing and forging were carried out [8-14]. It was demonstrated that at the speed of 1500-1750m/s a single water projectile having the mass of 350-400 g readily demolishes a concrete plate 16” thick and a reinforced concrete plate 30 cm thick. When a concrete plate was protected by a steel sheet the projectile pierced the steel and broke through the concrete. The water projectiles also successfully forged and pierced steel and other metals. At a lower speed the impact did not result in the concrete demolition. However, the damage accumulation in the course of several impacts brought about concrete fracturing.

While effective granite demolition was achieved at the water speed of 1000 m/s, the process could be significantly improved if the projectile speed is increased up to 4-5 km/s. The performed computations showed that this speed could be attained as the result of process optimization.

2. EXPERIMENTAL PROCEDURE

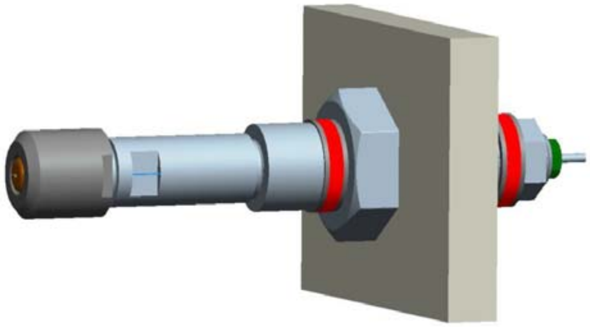

Figure 1. Launcher of high-speed water projectile.

The experimental technique involved impacting of a granite half-space by a sequence of water projectiles and subsequent examination of the generated cavities and debris. It also included the use of high-speed imaging technique for estimation of the projectile velocity. The nozzle diameter was 2 mm and the estimated projectile speed changed in the range of 1000-1050 m/s. The amount of a powder charge was fixed within tolerances of commercial factory-loaded blanks. Accuracy of water load mass was assured by loading with a syringe. Prior to firing the standoff distance and the position of the impact zone were determined. The shots resulted in formation of holes in a granite plate. In the most cases, when it was possible, the volume and the geometry of the generated cavities were measured. The volume, which determined the amount of the granite removed, was measured by filling the cavity by water and subsequent water extraction by the syringes. Because of water absorption by and penetration through the cavity wall the measured water volume, that is amount of the granite removed, were below the actual value. An error of such estimation will be determined later. The geometry of the cavity was estimated by the cavity depth and the dimensions of the surface area. This area was approximated by a circle or an ellipsis.

The initial phase of the work involved design and construction of a launcher and launcher integration in a setup for granite demolition. The launchers (Fig.1) having the exit nozzle diameter of 2 mm were used. The maximal water load of this launcher was 8g . The attempt to load 8.5 g water resulted in powder wetting. Of course, any reduction of the water load below 8 g was trivial. The 0.38 caliber Winchester rounds were used in the performed experiments. The powder load of a round, equal to 1.2 g was the energy source of the process.

Figure 2. Modified Remington Power Tool.

Because the powder massthat is the energy consumption per a shot, in the launcher above was constant, another launcher (Fig.2) was used to investigate the effect of the energy change. This launcher constituted a modified Remington power tool and was used in the previous study of the projectile formation, performed by NJIT Waterjet laboratory. It is important to notice, that while the launcher Fig. 1 used the combustion products as a driving media, in the launcher Fig.2 the water load was driven by a moving piston. The difference of the water acceleration mechanisms had limited effect on the projectile properties which were completely determined by the boundary conditions and the channel geometry.

During the experiments the launcher was held by a special vice while the granite plate was supported by a moveable base. The position of the base determining the standoff distance was precisely controlled (Fig.3). The experiments were carried out in an isolated cabin equipped by a continuously operating exhaust.

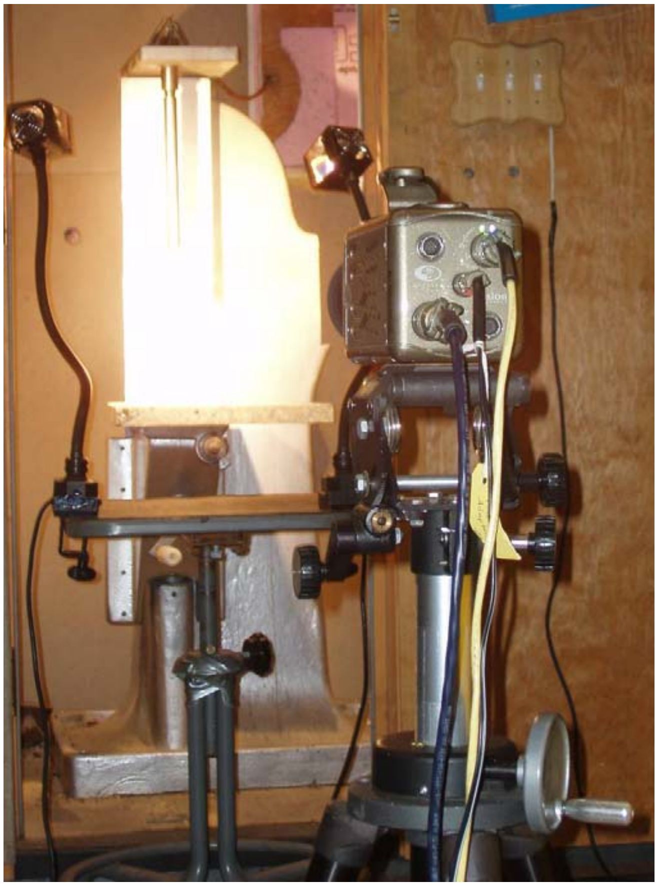

Figure 3. Experimental setup for investigation of high-speed liquid projectiles.

3. EXPERIMENTAL RESULTS

3.1. Experiment 1: Investigation of the effect of the standoff distance on the granite excavation. (Figs 4-6). The objective of the experiment was to determine an available range as well as an efficient value of the standoff distance. In the course of this experiment a granite plate was impacted by a water projectile at different SODs. The resulted volume of material removed and the size of the generated pit were measured. The experiments were carried out at the identical conditions (1.2 g of powder, 8 g of water, and the same kind of granite).

In the course of this experiment it was found that at SOD less than 150 mm the excavation rate of 1 cm^3 was exceeded almost in all cases (Fig.4). A noticeable material removal occurred up to the SOD of 266 mm. This was the maximal SOD attainable in the given experimental setup (Fig.3). Because the most stable material removal was achieved at SOD=6 mm, this SOD was used in the most of the following experiments.

The enhanced granite removal ($v>10$ cm^3) occurred in 3 cases (Fig. 5), while the weak ($v< 1$ cm^3) material excavation took place in 8 cases (Fig.6). The observed process performance in both cases was similar thus it can be expected that the difference in material removal was due to the peculiarities of the granite structure. The conditions which assure enhanced and prevent weak projectile performance will be determined in the following study.

3.2. Experiment 2: Investigation of the effect of a water load on the material removal. The objective of this experiment was to estimate a near optimal value of the water load. The performed experiments showed the steady increase of the absolute and specific rates of the material removal, as the water load increased (Figs 7 and 8). Because at the selected launcher design the water load was limited to 8 g, this amount of water was used in the following experiments. It is expected that increase of the water load will increase the boring rate.

3.3. Experiment 3. Investigation of the granite boring: same site impact. (Figs 9-11). The objective of this experiment was to estimate the superposition of the sequential impacts. Experiment 3 involved investigation of the dynamics of the granite removal at impacting a same site of the target. In the course of the experiment the mass of powder was 1.2 g per a round and the water mass was 8 g per shot. The results of the experiments are shown on Figs 9 and 10. As it is demonstrated by these figures both the depth of the penetration and the rate of the excavation rapidly decrease as the depth of the cavity increases. The acquired information is not sufficient for the explanation of the cause of this decrease, which will be explained in the course of the further study.

3.4. Experiment 4. Investigation of the granite boring (Figs. 12, 13)**.** The objective of this experiment was to demonstrate feasibility of generation of a channel of a desired length and 2.5” in diameter. A sequence of projectiles impacted the surface of a granite plate. These impacts enabled us to remove the first layer of the granite. The following second, third, etc. layers were removed similarly. It was possible to measure amount of granite removal only for first 26 shots. The rate of removal was around 1 cm^3 per shot. While the objective of boring was to create a cylindrical channel and the granite removal had to be limited to the area within the channel boundary, a significant amount of granite was removed from the regions outside of this channel. This unwanted excavation could be prevented by the proper nozzle positioning in a boring head. In the final analysis this experiment demonstrated feasibility of the boring a 2.5” channel by the projectiles generated by a 2 mm nozzle.

3.5. Experiment 5. Investigation of the granite boring using distributed impacts (Figs. 14-17). The objective of this experiment was to investigate enhancement of the granite removal due to superposition of the effects of two or more neighboring impacts. In the course of this experiment a target was impacted by several projectiles at different locations and at a different sequence. The impact sites were distributed as a Cross, Line and Triangle. Each site was impacted once or twice.

It was found that two consecutive neighboring impacts were more efficient than consecutive shooting at the same site. No choking effect (decrease of the rate of removal as the depth of a cavity increases), noticed for the impacts of a same spot, was observed in this experiment. Further enhancement of the material removal was recorded when three spots arranged in the equilateral formation were consecutively impacted. In this case only two first shots at one corner of the triangle resulted in the penetration at the depth of 38.71 mm. The enhancement was evident in the volume increase as well. Consecutive impacts of neighboring spots increased efficiency of excavation. It was noticed that first four shots removed about 8 cm^3 of granite. However, as the depth of excavation increases the average granite removal becomes 1 cm^3 per shot. The overall result can be enhanced further by optimization of standoff distance and by optimal positioning of the nozzle.

3.6. Experiment 6. Investigation of the effect of the stresses induced on a granite target. (Fig. 18) In the course of this experiment granite plate was exposed to compressive stresses induced by four vices (Fig. 18). As a result the rate of material removal of 2.6 cm^3 per shot was attained. Thus effectiveness of the granite boring under stresses was demonstrated.

3.7. Experiment 7. Investigation of the granite removal using a low power projectile. Because the safety consideration precluded change of powder load in the course of these experiments, another launcher (a modified Remington power tool) was used for granite removal. The powder charge in this case was 0.3 g and the water load was 4.2 g. The specific rate of granite removal in one of experiments was 2 cm^3 per 1 g of powder. This result exceeded in two times the specific rate of removal (1 cm^3 per 1 g of powder) at a larger charge. While in former the water-to-powder ratio was 4.2/0.3=14 g/g in the later this ratio was 8.0/1.2 =6.67 g/g. While the increase of the impact effectiveness can be at least partially determined by the powder properties, the effectiveness of the optimization of the energy-to-working fluid mass ratio (the specific energy of the process) was demonstrated.

3.8. Experiment 8. Investigation of marble removal by a water projectile. (Fig. 19). In order to examine the boring other than granite materials a marble plate was impacted by high speed liquid projectiles generated by the Remington power tool. The performed experiments showed that due to marble ductility the rate of the marble removal was almost two times less than that of the granite.

3.9. Experiment 9. Investigation of size distribution of the granite particles generated in the course of a single shot.

The debris generated in the course of an impact was collected. The observed distribution of the particles size shows the feasibility of the debris excavation from the impact site.

3.10 Experiment 10. High speed filming of the projectile motion.(Fig. 20). A high speed camera Phantom V-7 of Vision Research Incorporated (30,000 frame/s and 150,000 frame/s) was used to acquire digital images of projectiles (Fig.20). The observed speed of the projectile head was 539 m/s immediately after leaving the nozzle. Then the speed of the projectile head increased to 865 m/s at 14 cm away from the nozzle and reached 1065 m/s at the impact zone. The variation of the velocity of the head of projectile was similar for both launchers. However high removal rate for the launcher Fig 2 shows that the average velocity (momentum) of its projectiles is higher.

4. EVALUATION OF THE FEASIBILITY OF THE USE OF A LAUNCHER AS A BORING TOOL

Let us assume that it is required to bore a granite layer and to generate a tunnel having the diameter of 2.5” and length of 1 m. Total volume of the granite to be removed is

$100*3.14*7^2/4\sim4000$ cm^3.

In the course of the performed experiments it was found that in order to remove 1 cm^3 of granite it is necessary to spend 1.2 g of a powder and 8 g of water. Thus removal of 1 cm^3 of the granite required 10 g of fluids. If the media consumption during the operation will be the same as during the experiments then the total required amount of the media is

4000*10=40,000 g =40 kg of the media.

Let us now estimate the required process duration. Because 1 shot brings about removal of 1 cm^3 of granite, removal of 4000 cm^3 will be accomplished by 4000 shots. Thus the launcher should fire 4000shots. A numerical modeling of the launcher operation shows that the duration of the explosion/expulsion process required 1-2 milliseconds (Fig.21). Thus the process can be carried out at the firing rate of

1/0.002=500 shot/sec=30,000 shot/min.

It is necessary now to estimate feasibility of the launcher operation at such firing rate. An internal combustion engine can operate at a rate of 10,000 combustion cycles per minute. Because the only moving part of a launcher is a check valve it can be assumed that such frequency is also attainable by a launcher. Thus it is assumed that the operational firing rate will be 10,000 shots/min rather than 30,000 shots/min. At the selected frequency the duration of the firing 4000 shots that is the process duration is

4000 shots/10,000 shots/min=0.40 min.

Thus, the estimated duration of the excavation will be below1 min. However, the actual weight of the required working and energetic fluids as well as the process duration could be below these estimations. Even in the course of the performed experiments it was found that the rate of the removal can be as high as 10 cm^3 per 1 g of media (Fig. 22). It is 10 times more than mass removed used for the above estimation. Then, the high frequency movie shows that the speed of a projectile at the impact zone was 1000 m/s. The projectile speed of 1750 m/ was already attained in the course of the previous experiments. A numerical analysis (Fig.21) shows that the speed of the projectile can be as high as 5-6 km/s. It is expected that the optimization of the launcher operation will enable us to accelerate the projectiles to the speed of 3000 m/s. Thus the kinetic energy of the impact and, correspondingly, the rate of granite removal, will be at least 10 times more than that observed in the performed experiments. Consequently, optimization of the conditions of the projectile formation as well as the projectile-workpiece interaction at least theoretically enables us to increase the specific material excavation. Thus the estimated weight of the media (40 kg) and the process duration (1 min) are realistic.

5. CONCLUSIONS

5.1. The feasibility of the granite crushing by high speed (1000 m/s) water projectiles was demonstrated.
5.2. The feasibility of formation of a channel 100m*2.5” during 40 min or less using about 5000 kg of the working media was shown
5.3. The generated debris is suitable for excavation
5.4. The effective crashing occurs up to the standoff of 75 nozzle diameters (150 mm at the nozzle diameter of 2 mm).
5.5. The induced stresses and previous damage significantly enhance granite excavation.
5.6. The following issues should be additionally addressed:

5.6.a. The existing launcher design which resembles the design of a rifle is not suitable for the desired boring operation. The launcher should generate pulse stream, where the amplitude of each pulse (the maximal speed of a projectile) should be in order 2-4 km/s.

5.6.b. Currently a launcher operates as a rifle using a round as a source of working and energetic fluids. Such mode of operation is not suitable for high rate deep boring. The launcher should use only liquid media.

5.6.c. While the use of different working and energetic fluids is feasible it dramatically increases complexity and thus dramatically reduces reliability of the boring head. A single mixture of fluids or slurries must be supplied to the launcher.

5.6.d. While a room temperature projectiles are suitable for crashing and pulverization of brittle materials they could not fracture ductile materials, e.g. steel bars. It is necessary to generate high temperature impact zone to enable us to excavate ductile materials.

6. NOMENCLATURE

m_c-mass of powder, g
SOD-standoff distance, mm
t-depth, mm
v-removed volume, cm^3
w-mass of a boring media (water),g

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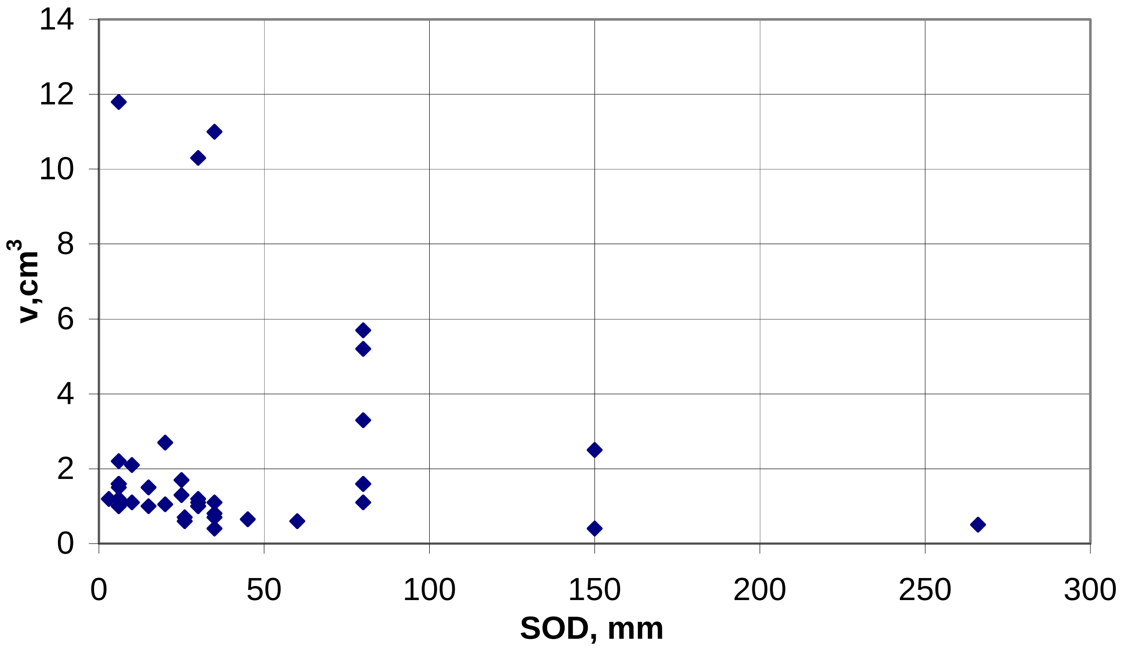


Figure 4. Effect of the standoff distance on the granite removal

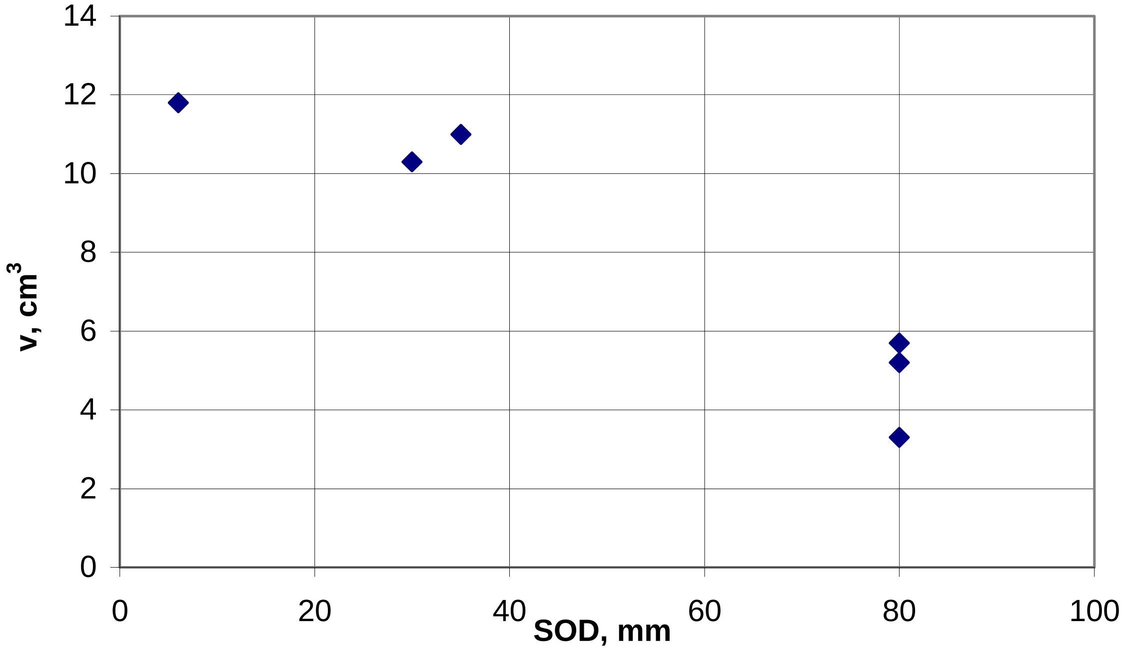


Figure 5. Effect of the standoff distance on the granite removal (High removal rate)

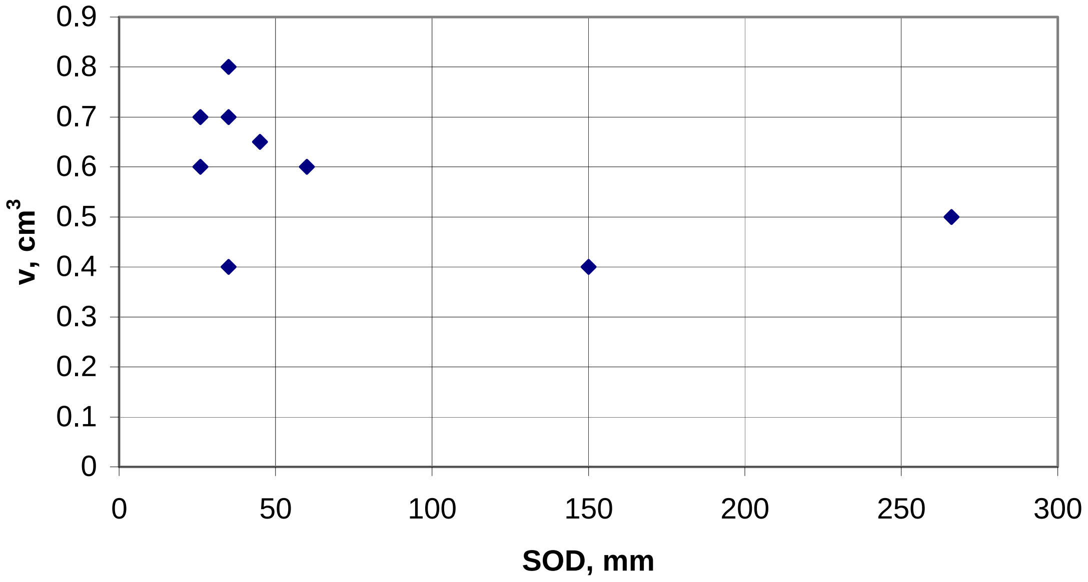


Figure 6. Effect of the standoff distance on the weak granite removal (Low removal rate).

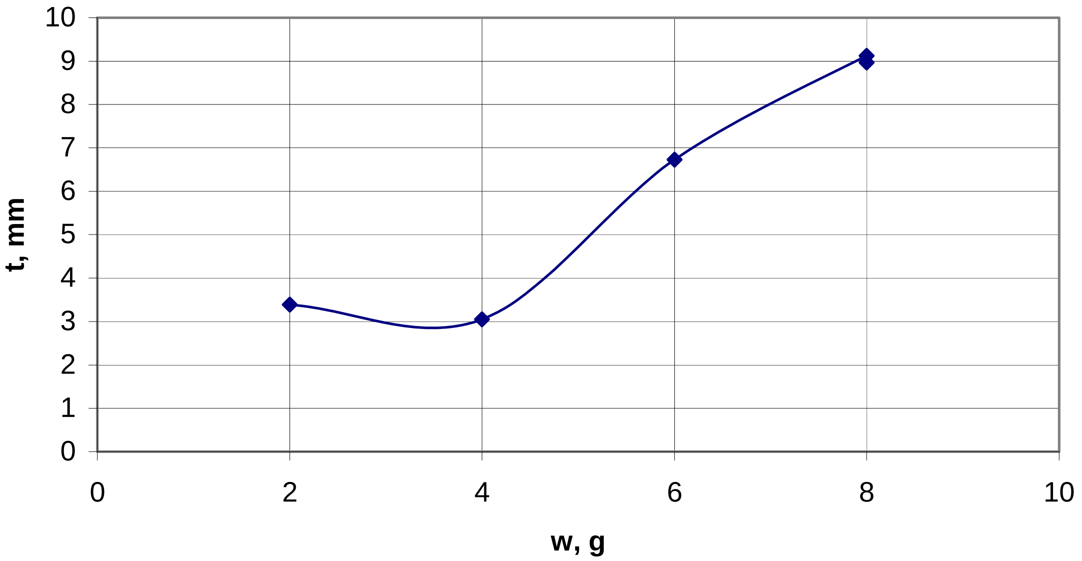


Figure 7. Effect of the water load on the depth of penetration

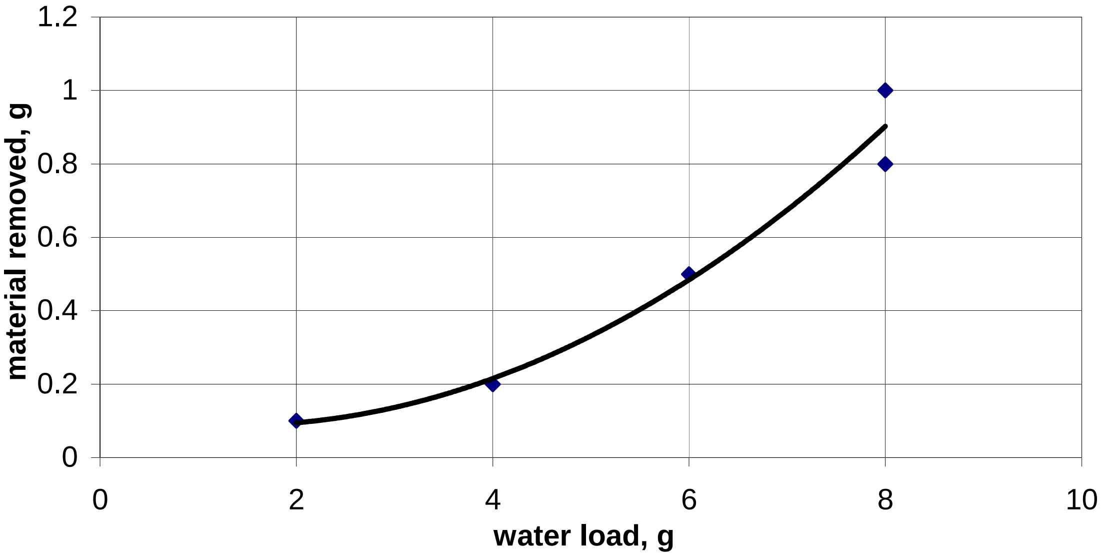


Figure 8. Effect of the water load on the granite removal

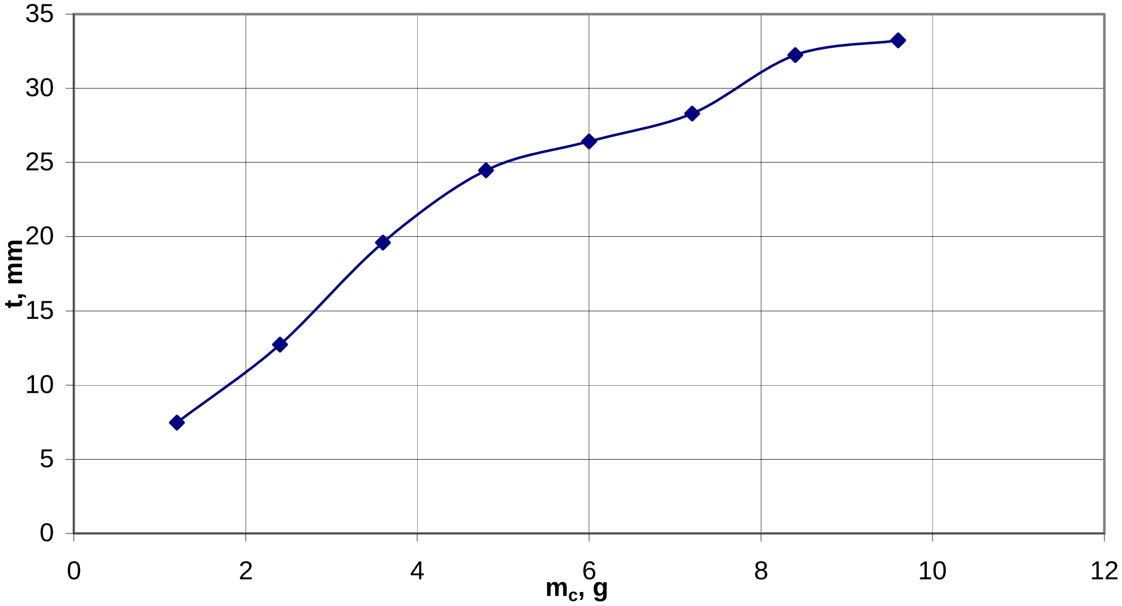


Figure 9. Effect of cumulative (total) powder consumption on the depth of penetration

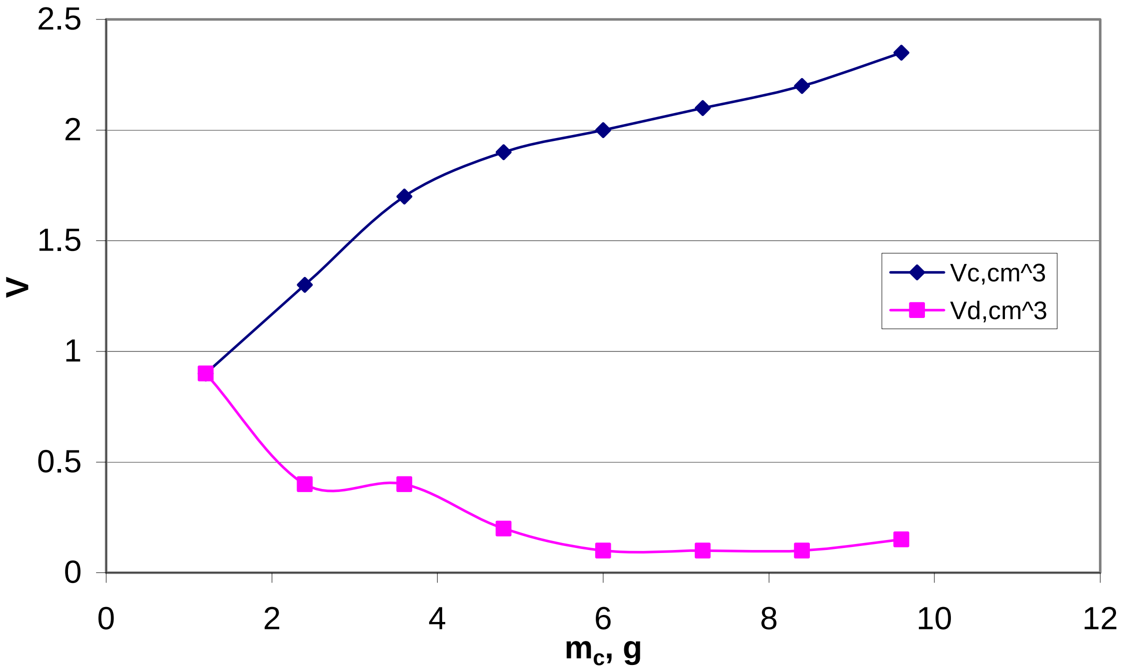


Figure 10. Effect of total (cumulative) powder consumption on the granite removal Here Vc-total removal, Vd-granite removal per a shot.

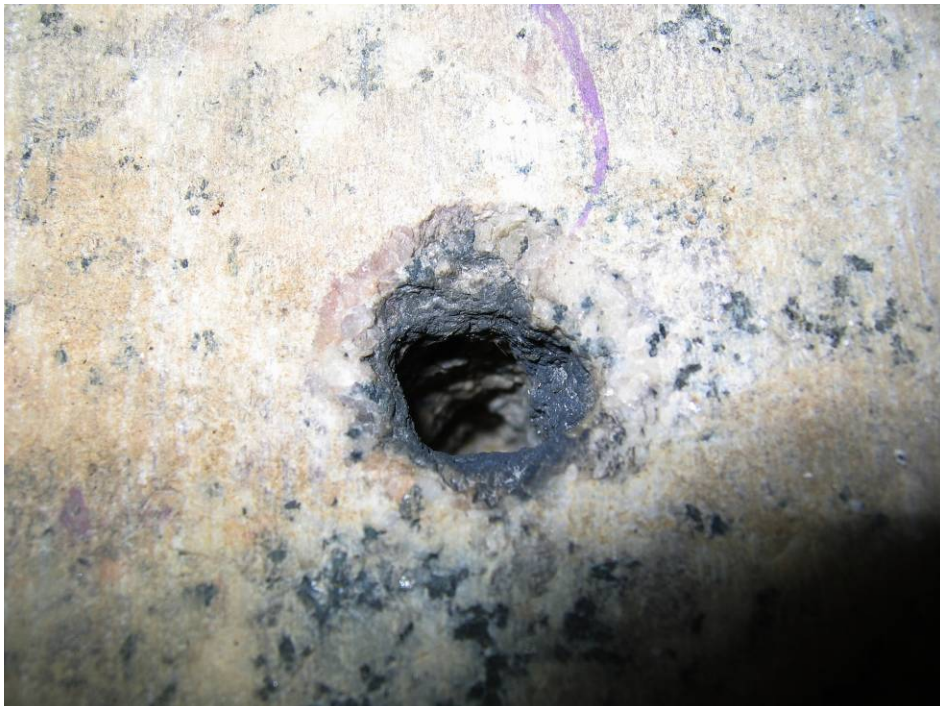


Figure 11. Boring of a granite plate by sequential impacts of projectiles at the same site.

Figure 12. Boring of a granite by 52 sequential impacts.
Notice dimensions of the generated cavity.

Figure 13. Boring of a granite by 52 sequential impacts.

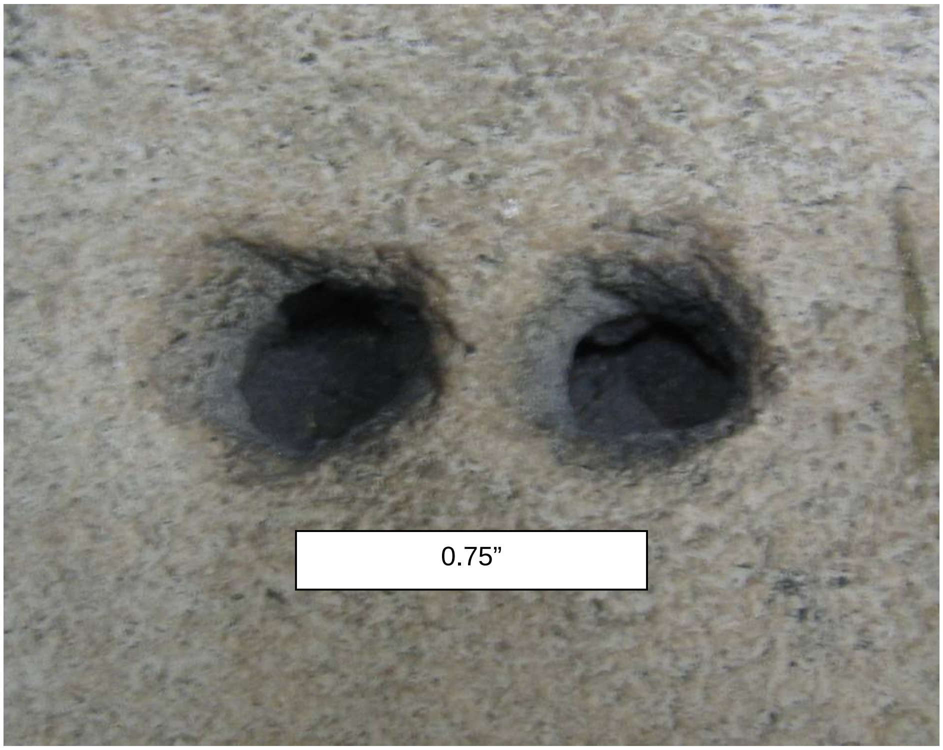


Figure 14. Two impacts with the distance of ¾” between axes of the impact zone. Notice absence of interference.

Figure 15. Three impacts at the distance of ¾” between axes of impact zones. Notice minimal interference.

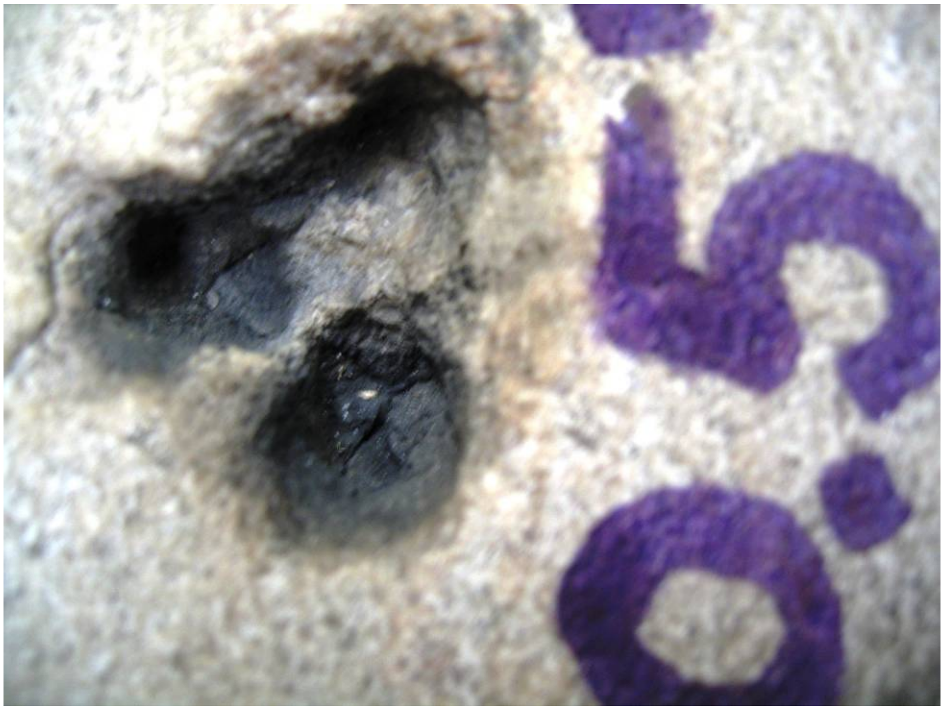
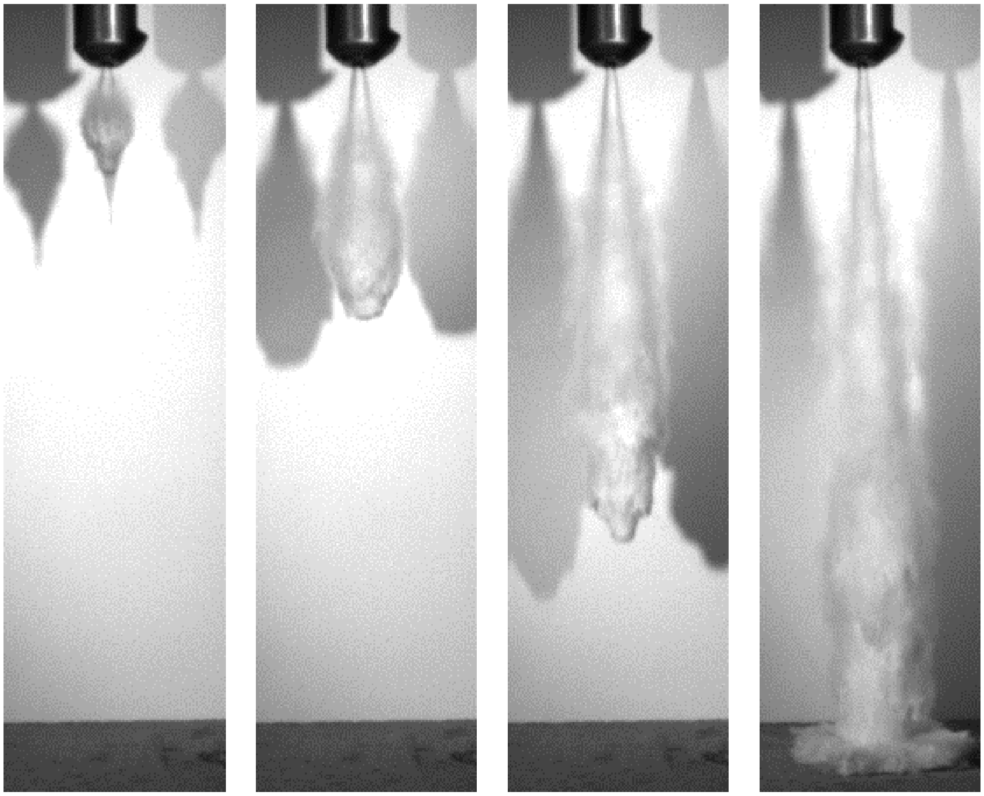


Figure 16. Three impacts at the distance of ½” between axes of impact zones. Notice significant interference between two shots.

Figure 17. Boring of a granite plate by sequential impact with a cross-like pattern of impact distribution.

Figure 18. Setup for granite boring at induced compressive stresses.

Figure 19. Granite removal by impact of a projectile generated by low-power launcher.



135μs 27mm | 226μs 66mm | 316μs 138mm | 452μs 266mm

Figure 20. Development of a water projectile in air.
The distance above is the distance from the exit of the nozzle.

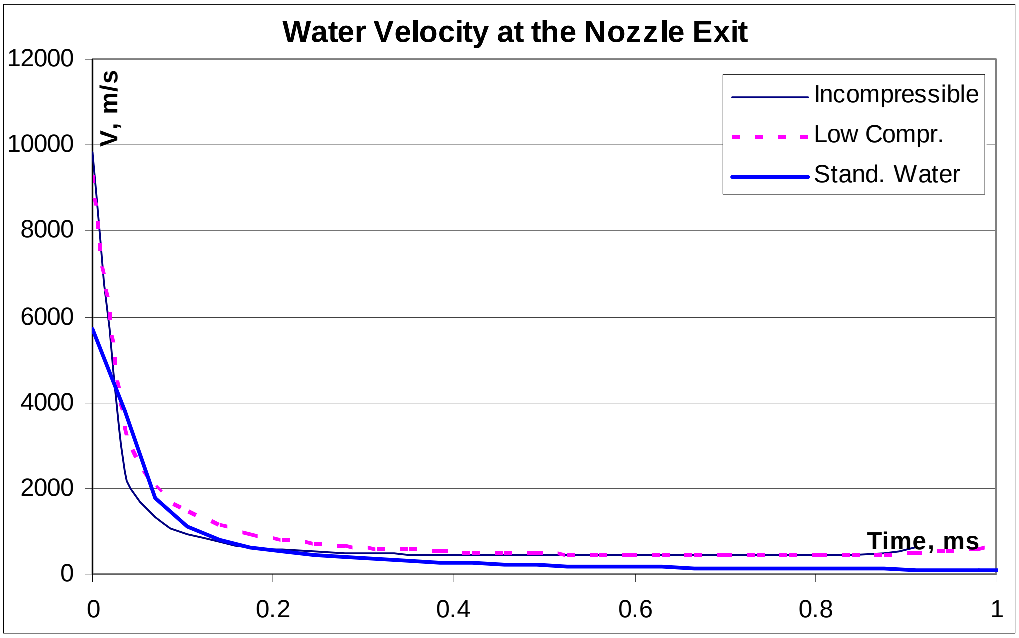


Figure 21. Numerical modeling of the variation of the water velocity at the launcher exit,. Notice that the speed of the water at the head of the projectile was as high as 5,500 m/s.

Figure 22. Impact of a granite plate at SOD=80mm.
Notice intensive granite removal in the course of this impact.