Deep Water Excavation with Shaped Charges A Case History in Lake Mead

By Roberto Folchi and Hans Wallin

Lake Mead, the largest man-made reservoir in the United States, is located about 30 miles southeast of Las Vegas, Nevada. For the construction of Lake Mead's third water intake, which is entirely placed underground, an underwater excavation was needed at a depth of 100 m (330 ft): a large surface had to be deepened by 20 m (66 ft) in basalt.

New technology that would fit the special circumstances of this job was not available, so the old one, the "brutal", not-precise but effective technology of the shaped-demolition-charges was chosen. It was then found that no shaped charge existed that fit the underwater specifications of this job so a new one had to be conceived, as well as its deployment system and technique, monitoring and survey procedures. For this, an international task of experts was put together.

Basaltic stone is strong and resilient. It has a high resistance to metallic jet penetration, close to that of ceramic which is therefore used in the defense industry on steel tank armor, to add extra protection to the penetration of the grenade's jet. High energy of the jet produced by the detonation of the charge was required for basaltic stone and, for this, an adequate liner material, the best quality of execution, right form and mass as well as an adequate stand-off in air were needed. To keep the charge stand-off water free at that depth, a specially fitted shell had to be coupled to the charge, ballasted to prevent floating. This was one of the "rings" of a chain of "problems to be solved" both in the design phase and also with work in progress, targeting to optimization of the production technology, of the product itself and of the method of use.

Since large quantities were needed, a solution targeted to minimize environmental impact was adopted. Biodegradable materials were chosen to reduce from one hundred years to five, the bio-degradation time of the plastic residual from the charge canister.

This article describes the development process, application, and results.

Rock mass outlines

The rock mass to be excavated was a basalt, mainly composed of plagioclase. More than one layer of basalt was expected to be found in place, probably erupted shortly in sequence so that no interposed weathered zone was expected.

An upper layer of stones, sand and silt was found in place and thickness quantified by means of sub bottom profiling (sonar) and mechanical coring.

Progressive increase of density from the top to the bottom of the loose sandy-silty formation and from this to the upper layers of basaltic rock weathered (it was exposed to the atmosphere before being covered by water after the Hoover dam completion) reduced accuracy leading to overestimation of the thickness of the loose materials overlaying the solid rock. A general view of the consistency of the rock to be blasted was possible through the open air survey of an outcrop in the nearby village of Callville **(figure 1)**. Rock mass appeared to be fractured within three main families of thermal shrinkage joints. Some faults were also noticed. Joints and faults singled out volumes ranging from a few cubic decimeters (some tenth of cubic feet) to some tenth of cubic meter (some cubic feet). Some joints showed earth filling but, into the rock mass, they were generally well closed. Non-interconnected cracks were noticed in the rock matrix.

Vesicular (closed porosity) basalt was noticed in the upper part of the formation with some large voids in the crown. The upper part, for a thickness of about half a meter (1.5 ft) was weathered with oxidized surfaced and slightly loose joints. Density of the rock was about 28 kN/m^3 (175 lb/ft^3) and weight per unit volume about 27 kN/m^3 (160 lb/ft^3). This formation, due to its high consistency and resilience, opposed strong resistance to the penetrating and fracturing action of the charges. Fractures and joints, well closed in the rock mass, also determined a less favorable condition for the cratering action of the charge.

Figure 1. Callville, outcrop of the rock to be excavated.

Excavation

An upper standing layer of stones, sand and silt was removed by air lifting and clam shell.

Material was mucked aside by swinging the drag line boom with bucket / clam shell kept below the water table.

The hole in the rock (needed to host an intake shaft/riser) was excavated by means of a shaped demolition charge, a "fragmentator" designed and engineered for the purpose.

Excavation progressed from the sides to the center of the hole with care taken to maintain slopes as straight as possible. Rock was broken by rounds of charges simultaneously ignited by means of a web of detonating cord. Detcord circuit had redundant cross connections in order to minimize risks of undetonated charges due to cord sections desensitized after water leaked through holes in the jacket.

Because of the water pressure at that depth, sealing for water tightness was an issue. Self-fusing tape was used to seal detcord ends to prevent watering and desensitization of the PETN. A shock tube detonator was used to ignite the circuit. Also this was sealed with self-fusing tape to prevent risks of leaking into the detonator cap through the crimp (too tight crimping could have interrupted the fire into the shock tube to the primary charge into the detonator cap).

No divers were needed. Charges were attached to a steel frame and deployed, being monitored via cameras and sonars.

Geo-referenced positioning of the charges was performed by RTK-GPS. This was also linked to an underwater tracking system USBL (Ultra Short Base Line technology) which was expected to give a precision of less than 1 meter (3.3 ft).

The charge patterns ranged from 1.5 m x 1.5 m (4.9 ft x 4.9 ft) to 0.9 x 0.9 m (3 x 3 ft) or also 0.9 x 1.2 (3 x 4 ft). The crater created by the blast had the form of a flat lens. Crater depth was detected with the underwater survey (multibeam sonar) to be of about 75 cm (2.5 ft), up to 1 meter (3.3 ft) with a max of 1.5 m (4.9 ft). Up to four fields per day were blasted. Fragmented rock was removed as done for the overburden. To minimize overpressure in water, a massive air bubble curtain was used.

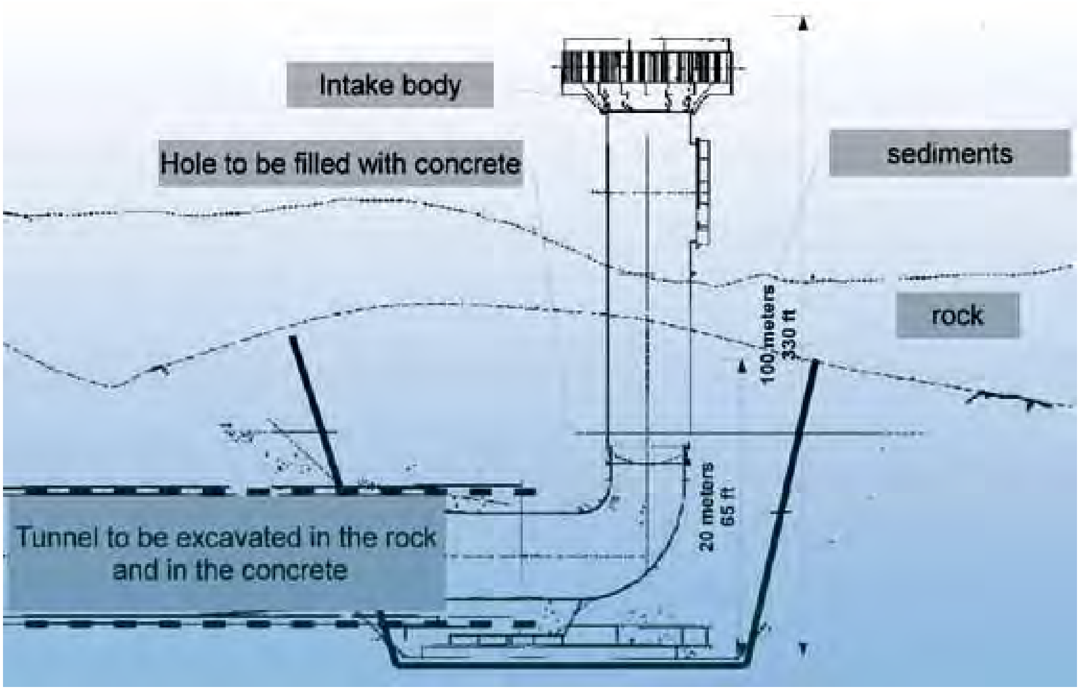


Figure 2. Lake Mead, third intake sketch.

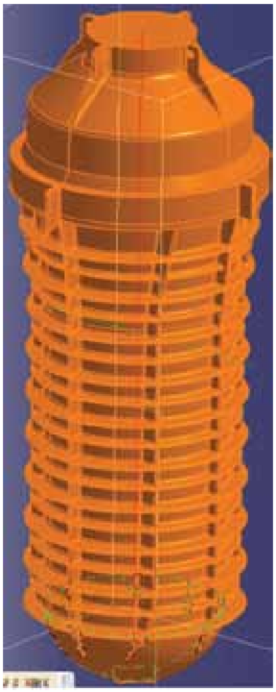


Figure 3. Design of the shaped - demolition charge.

Fracturing of the rock

After ignition of the charge, the detonation front starting from the ignition point became flat and hit the liner apex, focusing its energy on a point below and forming the liner into a slug. The slug hits the surface of the rock formation at about 4 km/s (2.49 mile/s) after having elongated itself in the 3 caliber stand-off, this due to velocity gradient among front and rear parts.

In its path it is not decelerated nor consumed by water which is kept aside by the bottomshell. The bottomshell geometry is such to compensate deviation of the jet slug trajectory due to eccentric ignition or deviation of the detonation front into the charge due to filling irregularities, voids and cracks.

A hole is formed by the impact of the 2.2 kg (4.9 lb) melted high density mass. Fractures extend radially from the hole, some of them connecting to the other produced by the adjacent charge and with the preexisting one.

Explosion gas flows radially from the charge, displacing water and moving downward to the rock and to the hole generated by the slug impact, like an "air cannon" through the path of less resistance in the "air channel" in the bottomshell. When explosion gas enters the crater, it extends the fractures generated by the slug impact as well as the preexisting fractures and by fractures intersections, it divides the rock mass in fragments and displaces them. Preexisting fracture and joints orientation influences the extension and geometry of the crater.

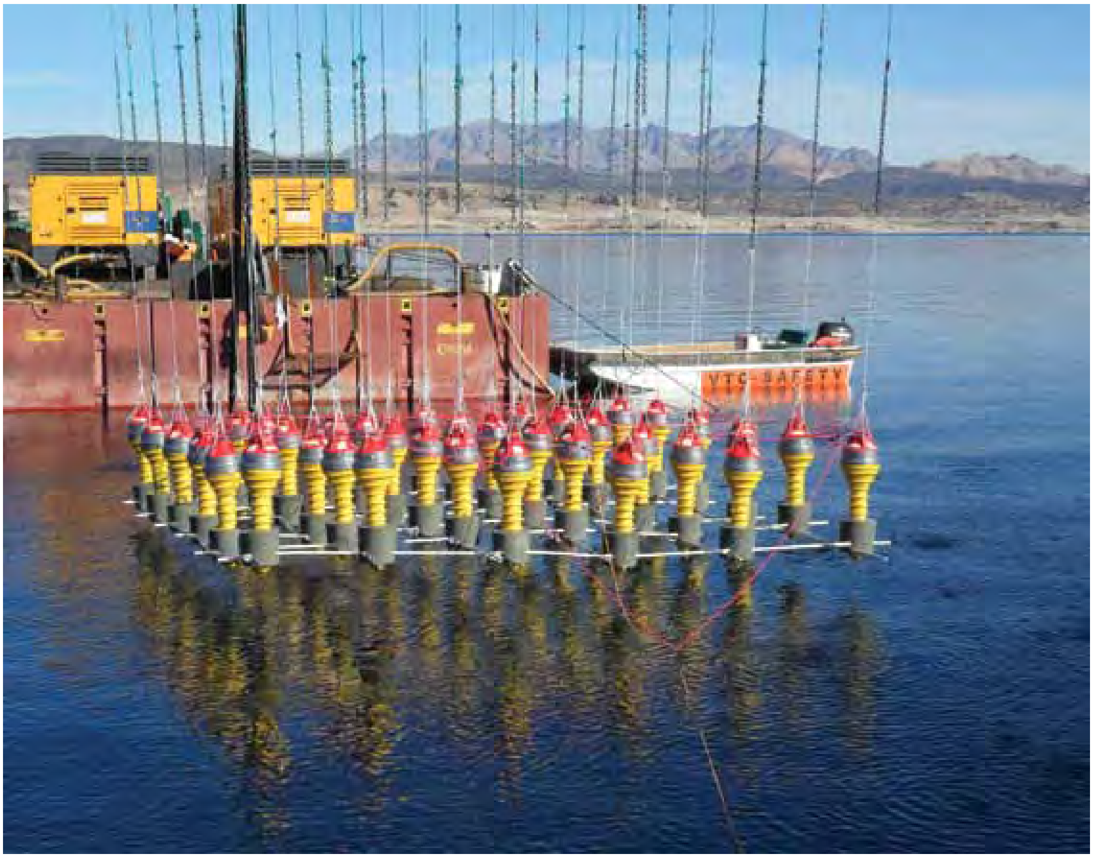
Expansion gas sweeps up the rock fragments from the hole and displaces the surrounding water, forming a large flat bubble. When the pressure at the bubble boundary becomes lower than that of the water column, the bubble collapses dragging back the rock fragments. Due to the compression of the water, the pressure of the bubble increases getting higher than that of the water column so it expands again and then collapses again, in a short sequence of pulsation damped in time of seconds. Explosion gas reaches the surface in small bubbles after about a minute. Fragmented rock is left in the immediate range of the blasting field and only a small fraction is found outside the blast field. Rock fractured below the crater remains in place and cannot be removed by means of the clam shell.

The shaped-demolition-charges-fragmentator

Since there was not a shaped demolition charge available that suited this underwater project, it had to be invented and engineered. Shaped charges were intensively used around the world up to 10 years ago for underwater blasting. Their use was primarily for depths exceeding 15 m (50 ft) when OD (overburden) drilling and blasting from a jack-up (a barge self-lifting on 4 legs) became an issue. They were also used in shallow waters to remove thin layers of rock (up to 2 m) as an alternative to the drilling and blasting which, for such a thin layer, requires high specific drilling (collaring). Due to the decline of marine work contracts, and also due to the increase in regulatory constraints to explosives projects, the use of shaped charges has been reduced, and as a result expertize and technology are getting lost. Not even the molds of the old charge canisters were found, either being lost or sold as scrap. It was so decided to start from the beginning, designing and engineering a demolition charge fitting the specifications for this project.

The first part to be designed was the liner. The form chosen was hemispherical instead of conical. The jet slug of a conical liner is faster, the hole produced is smaller and deeper, characteristics which are good for a "penetrator" charge but not for a "fragmentator" one.

Also hemispherical charges are less prone to misalignment of the ignition spot and to unevenness of the detonating front hitching the liner.



Figures 4 and 5. Charges on the barge, connected with detonating cord, with loops to absorb increase in distance when dropped in uneven lake bed. Net of detonating cord with redundant cross connections, ignited by a Pentolite booster. Plastic pipes kept charges standing at the right distance and to allow adjustment of the charge field to the uneven surface while keeping contact with the rock surface.

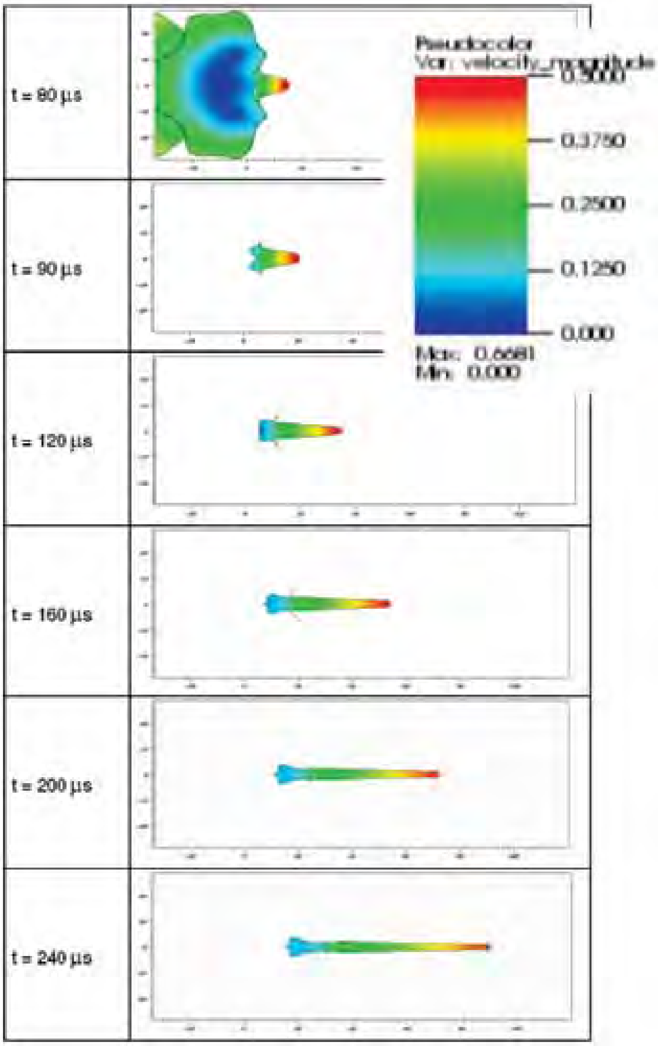


Figure 6 shows "GRALE code" computation of the jet slug produced by the detonation of the charge.

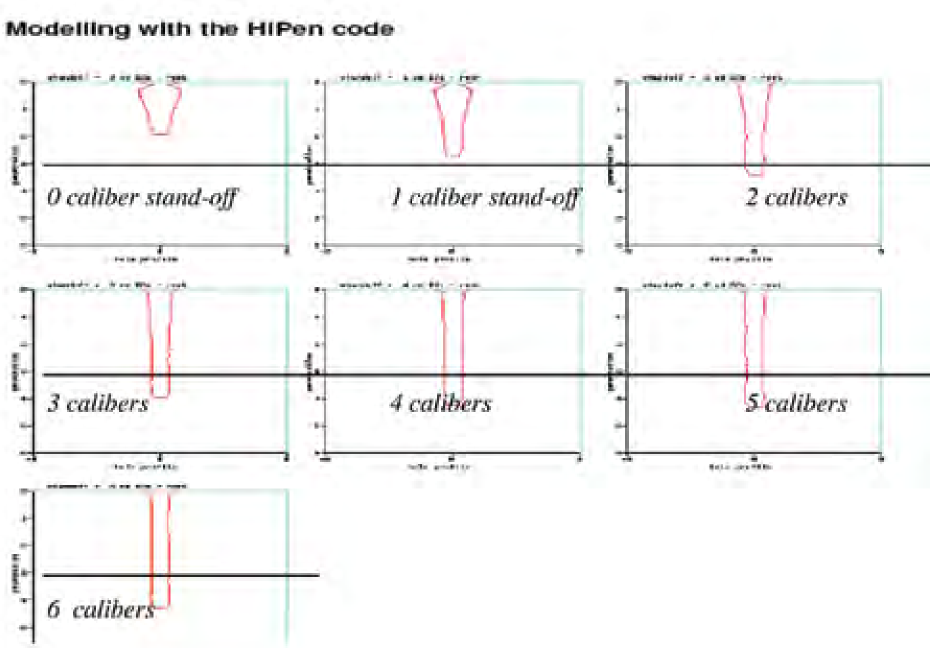


Figure 7. HiPen calculations of penetration in hard rock (basalt). Stand-offs are 0, 1, 2, 3, 4, 5, 6 calibers.

Referring to fundamentals of the optical-physic of the explosives, to maximize the detonation energy focusing effect of the liner, it was produced with a double curvature radius.

A heavy charge was originally specified: Composition B, 12 kg (26.5 lb), but the liner for such a charge was not easy to be cast, so the dimensions were reduced to 8.6 kg (19 lb). A special aluminum alloy was chosen as liner material, 2.2 kg (4.85 lb). A copper liner has a much higher penetration rate and fragmentation efficiency but it never became an option due to its higher cost and its non environmental friendly behavior in drinkable waters. Brand new Composition B was chosen instead of the demilitarized one considered in an earlier design stage. New Composition B would keep better control of homogeneity of the molten product and, by this, of the finished charge. A specification for the explosive filling was defined and a loading procedure was set together with the management of the filling facility in East Camden, Arkansas. Polyethylene was chosen for the canisters:

- uppershell, containing the explosive
- plug, needed to keep in place the booster and the detonating cord
- bottomshell, this last to be coupled to the charge – uppershell to keep the stand-off water tight.

As shown in **figure 7**, by computation of the hole produced by the slug impact, a stand-off bigger than 3 caliber would not have brought any relevant increase in depth. On the contrary it would have produced problems in the production of the bottomshell and also in ballasting the charge to give it negative weight underwater. That led to the decision to have a 3 caliber stand-off to be kept free from water, large enough to permit free elongation of the jet slug from the charge and to compensate misalignment of the jet axis from the theoretical one.

The form of the canisters had to be adjusted a few times to achieve the best results for maintaining long term water tightness at the intended depth. The FEM model used to predict resistance and deformations proved to be non reliable due to range in deformation tolerances and larger than expected shrinkage and also inconsistencies in the piece. This depended the local thickness, slenderness and distance to the ignition nozzle. Empirical adjustments were so performed. After a series of adjustments and tests in a hydrostatic chamber, finally a shell was produced, thin but strong enough to resist for more than one hour to the pressure of 100 m of water with a 1.5 safety factor (15 Bar, 220 psi). A biodegrading agent was added to the polyethylene grains before their fusion to reduce the biodegradation process of the bottomshell residuals left in the lake sediments after the blast (broken into little pieces but not completely burnt such as the up-

Figure 8. Broken rock mucked on the barge deck for sampling. Some old (brown) and new (gray) fractures could be noticed. The structure of the broken rock recalls that of the jointing seen in the open air outcrop on shore in Callville.

Figure 9. Muck pile underwater.

per part which is in direct contact with the explosive detonated) from about one hundred years to about 5 years.

Releases in water

- Concrete ballast: kg each charge: 30 (66 lb) pulverized
- Polypropylene, upper shell of the shaped charge, kg/charge: 1.0 (2.2 lb) burnt by the explosion shock wave and heat
- Aluminum of the lining: kg/charge: 2.2 (4.8 lb) oxidized

	RESULT	PASS CRITERIA
Impact Sensitivity (50% pt.)	31-60 cm , RDX: 7,5 N*m TNT: 15 N*m	> RDX (18-22 cm)
Large-Scale Gap (50% gap)	Test 201 cards	< Tetryl (238 cards) Comp B preferred (201 cards)
Friction Sensitivity	10/10 No Fires RDX: 120 N TNT: 353 N	20/20 No Fires at 250 lb
Electrostatic Sensitivity	10/10 No Fires	20/20 No Fires at 0,25 Joule
Vacuum Thermal Stability (at 100°C – gas evolved/g/48 hrs)	0,03 mL1	< 2.0 mL
Growth and Exudation	Grows as much as 6.9% when cycled between -54°C and +60°C6	< 1% volume change, < 0,1% weight change
Self Heating	190°C onset	T > 82,2°C (TNT component)
Detonation Velocity	7,9 km/s at 1,68 kg/dm3 RDX: 8,75 km/s at 1,82 kg/dm3 TNT: 6,90 km/s at 1,60 kg/dm3	
Heat of explosion (H_2O liquid)	Calculated: 5,2 MJ/kg RDX: 5,7 MJ/kg TNT: 4,5 MJ/kg Experimental: 5,6 MJ/kg	Test in pool.
Density	1,69 kg/dm3 MAX	
Melting point	80.2 °C (TNT component) RDX: 204 °C (it will not melt during production process)	
Volume of detonation gases	946 liters	
Deflagration point	230 °C (RDX component)	

Figure 10. Explosive characteristics.

- Polypropylene plus biodegradating agent, lower shell of the shaped charge, kg each: 6.0 (13.2) fragmented after the explosion
- Composition B reaction products, with reference to [Volk and Scheldbauer 1999]:

H_2	mol/kg 3.23	(1.5 mol/lb)	NO	mol/kg 0.02	(0.009 mol/lb)
CH_4	mol/kg 0.08	(0.036 mol/lb)	HCN	mol/kg 1.1	(0.5 mol/lb)
CO	mol/kg 8.99	(4.1 mol/lb)	H_2O	mol/kg 9.59	(4.35 mol/lb)
CO_2	mol/kg 4.08	(1.85 mol/lb)	soot	mol/kg 7.41	(3.36 mol/lb).
N_2	mol/kg 10.35	(4.7 mol/lb)			

Monitoring seismic waves

To keep track of the seismic waves induced by the blast, five triaxial seismographs were used.

Three were installed on land, one of them in the nearest piece of land, two on small island 400 and 600 m apart (440 and 650 yard). Two were installed on a barge, one of them standing over the blast field, the other one about 150 m apart. Power regression of the seismic monitoring on land showed a high level of confidence. Maximum peak particle velocity induced by the nearest sensible acceptor were 1/50 of the threshold given from the USA RI 8705 and 1/10 of those given by the German DIN 4150-3 (the most conservative of all). Seismic monitoring was therefore interrupted on land once having sampled a complete set of representative data.

Monitoring was continued on the barge in order to keep a record of the stress induced by the blast on the marine equipment and to collect data.

Accuracy of the power regression of the seismic waves measured on the barge is still good but not such as that of seismic on land, due to influence of the air-column raising from the air-bubble-curtain in the bottom which reduced randomly the density of the water and by this its elastic behavior and dumping factor.

Monitoring overpressure in water

Overpressure in water for each blast was measured by means of two tourmaline transducers, right over the blast. One of the two was placed close field and the other at distance. Density variations due to the random concentration of the air bubble raising form the air-bubble-curtain, as well as little variation of the data sampled in terms of distance and charge quantity, determined low accuracy in the power regression. The intense air bubble curtain proved to reduce significantly the peak overpressure. Less significant reduction was noted for the impulse.

Underwater survey and excavation progress assessment

Excavation was controlled by multibeam sonar survey. This was needed especially to check progress of mucking and performance of the charges.

To match locations surveyed previously and to be surveyed, location and orientation of the sonar head had to be assessed with accuracy in absolute coordinates. The sonar was so equipped with a positioning system consisting of a differential GPS on board, connected with a Real Time Kinetic GPS placed on land in a spot whose exact location was surveyed and marked in absolute coordinates. It was so possible to compensate the error induced in the GPS system by locating the survey boat, and by this, of the sonar head, in the range of centimeters.

Extra precision was needed to compensate for rapid variation in the orientation of the survey boat due to the waves and wind on the survey boat and was given by means of a "pitch, roll, yaw and heave unit".

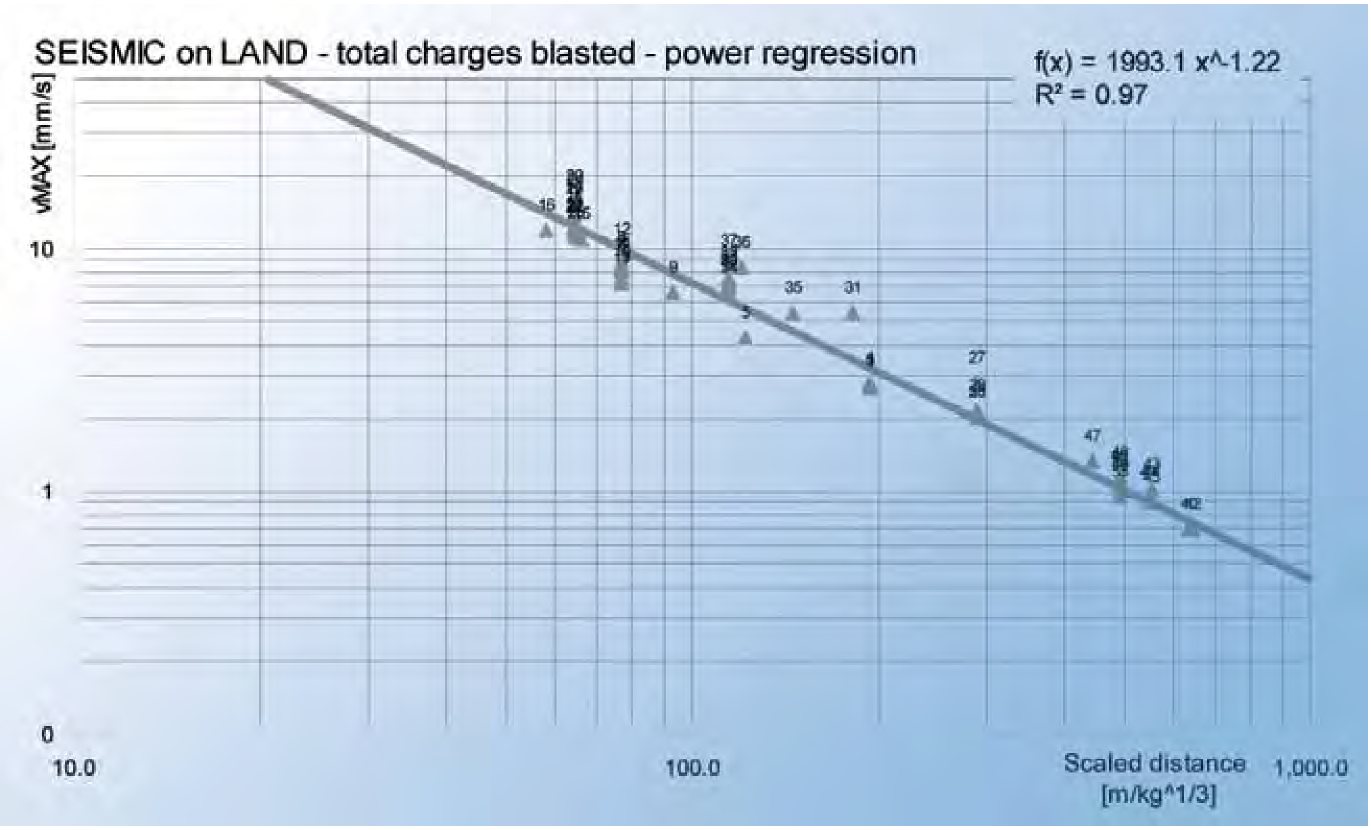


Figure 11 and 12. Blast induced vibration monitoring system and site decay curve.

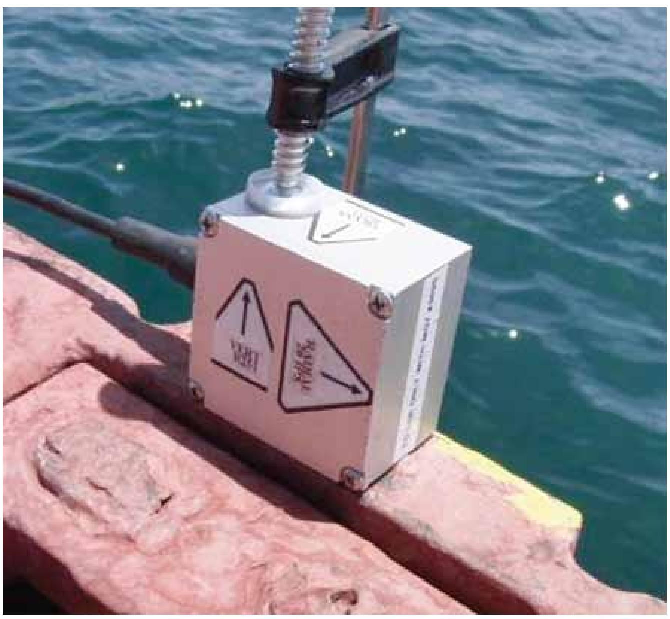


Figure 13, 14, and 15. Seismograph installed on the barge and decay curve.

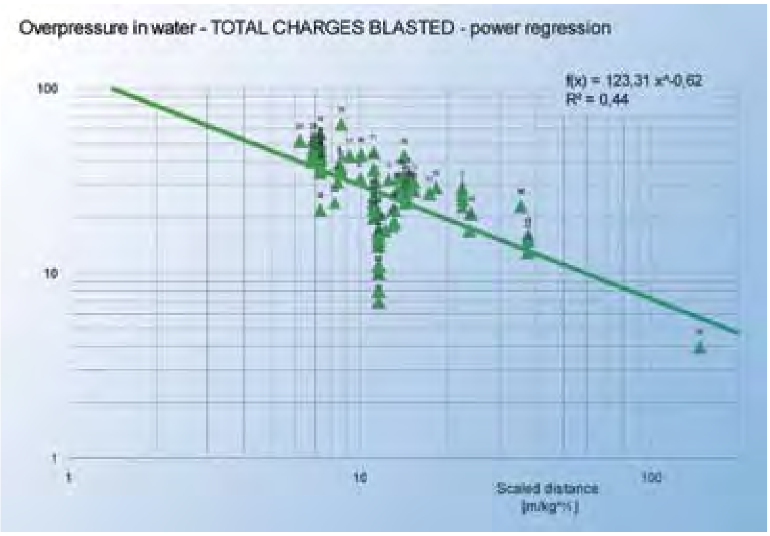


Figure 16 and 17. Overpressure in water.

Figure 18. The survey boat with D-GPS antennas linked to a RTK-GPS on land, for georeferences capture of the underwater profile with the multibeam sonar.

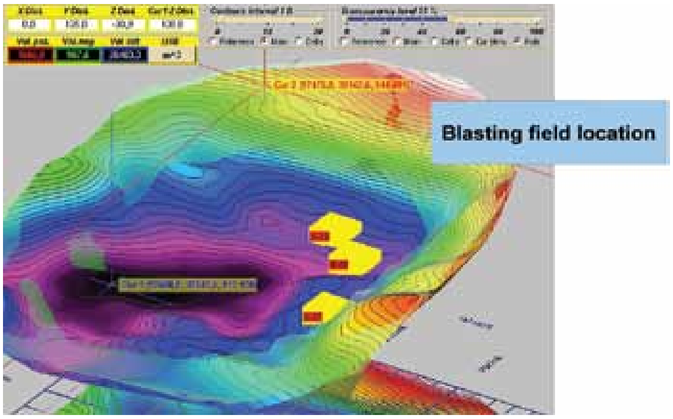


Figure 19. Output of the 3D matrix captured with the multi-beam sonar.

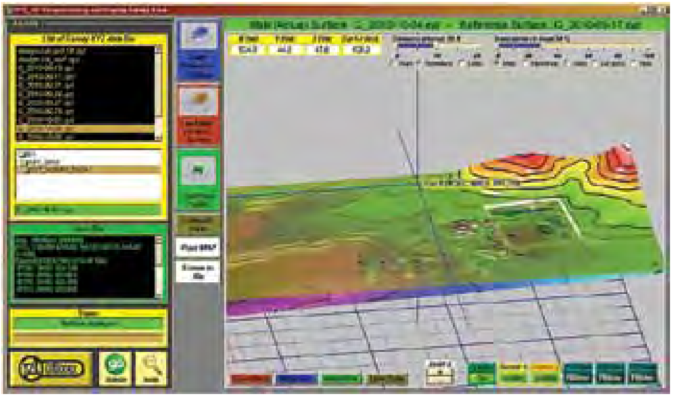


Figure 20. Post acquisition analysis to compare surfaces being captured at various stages of the excavation and also to compute volumes already excavated, volume to be excavated, depth of each single spot, inclination of the slopes, etc.

Conclusion

Thanks to the hard work of an enthusiastic team of old people with a passion for explosives and a spirit larger than its "casing", as well as to the trust of a company with a vision and a crazy attitude to almost-impossible-projects, it was possible in a short time, with a reduced budget and in lack of reference to a similar task, to conceive and put in practice a system to perform an excavation at 100 m depth in hard rock mass.

This confirms also that explosives can provide an effective solution to difficult tasks and that passion, cooperative attitude and expertise networking may permit results otherwise not possible.

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About the Authors

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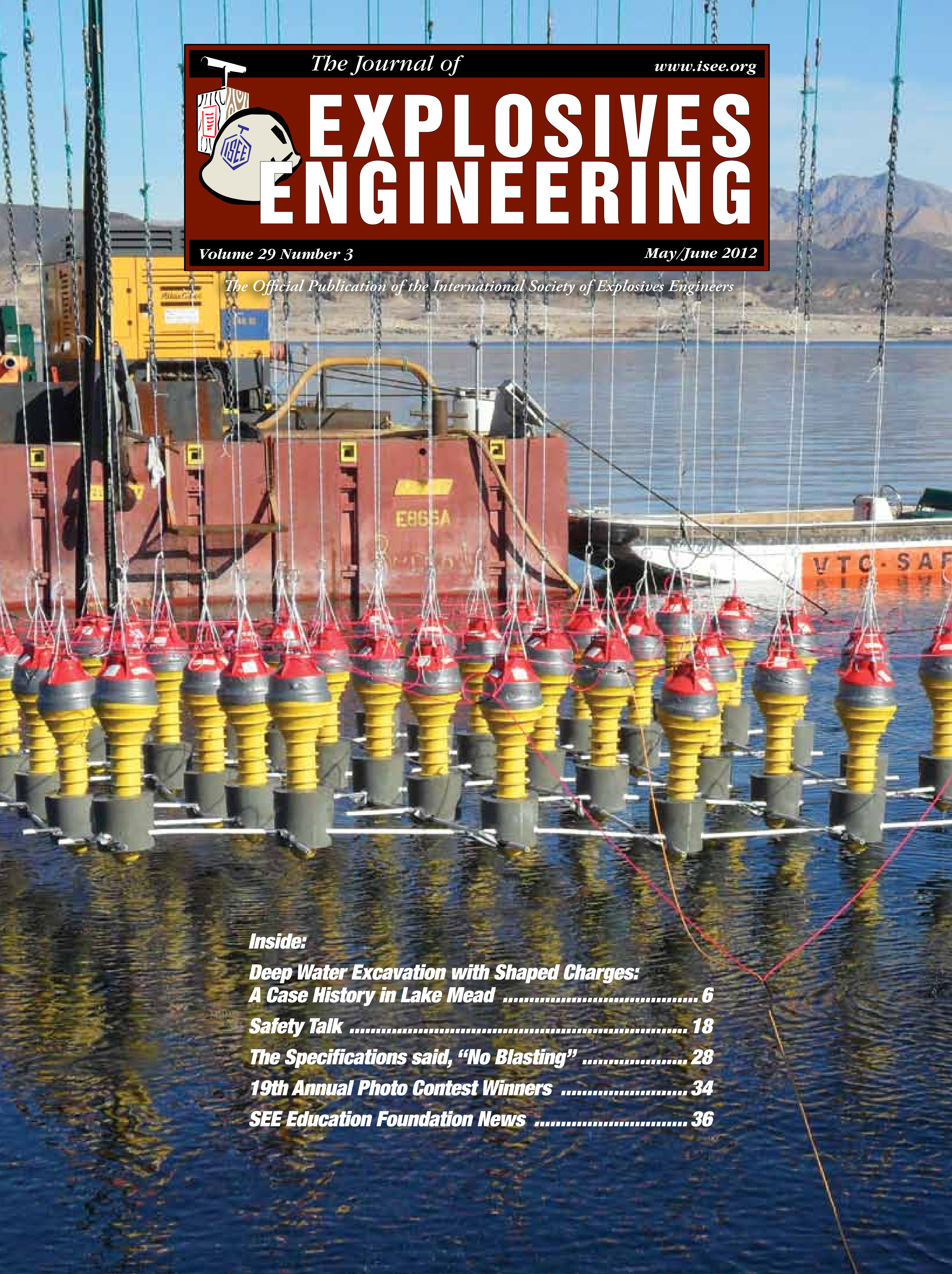

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