Conf-910435--34

SAND--90-2310C

DE91 006215

SAND90-2310C

MECHANICAL EXCAVATOR PERFORMANCE IN YUCCA MOUNTAIN TUFFS*

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ABSTRACT

A research effort of four phases is in progress at the Colorado School of Mines. The overall program will evaluate the cutability of welded tuff and other lithologies likely to be excavated at Yucca Mountain in the site characterization process. Several mechanical systems are considered with emphasis given to the tunnel boring machine. The research comprises laboratory testing, linear drag bit and disc cutter tests and potentially large-scale laboratory demonstrations to support potential use of a tunnel boring machine in welded tuff. Preliminary estimates of mechanical excavator performance in Yucca Mountain tuff are presented here. As phases of the research project are completed, well quantified estimates will be made of performance of mechanical excavators in the Yucca Mountain tuffs.

INTRODUCTION

The U.S. Department of Energy (DOE) has been conducting a program for siting the nation's first nuclear waste repository for commercial radioactive waste. The DOE has determined that the safest and most feasible method currently known for disposal of such waste is to emplace it in a mined geologic repository. Yucca Mountain has been designated for characterization as a potential site. This calls for a comprehensive and wide ranging program of detailed investigations to determine if the site is suitable for a repository. One of the relevant questions pertains to the applicability of mechanical excavation machinery to the site characterization activities. The purpose of the work described subsequently is to estimate the performance of various mechanical excavators through properties testing, linear cutting tests, large-scale bore tests and empirical modeling.

Mechanical excavations have several positive attributes when compared to conventional mining. Relative to drill and blast, mechanical excavation causes less ground disturbance, which could reduce support requirements and enhance stability of the repository openings, issues of importance during

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*This work was performed under the auspices of the U.S. Department of Energy, Office of Civilian Radioactive Waste Management, Yucca Mountain Project, under contract DE-AC04-76DP00789.

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the waste emplacement and caretaker periods. Bored openings with smooth walls and limited fracture damage could improve the post-closure performance of seals. Mechanical excavators potentially could be operated without introduction of fluids, which might contaminate the ground and adversely impact the accuracy of geochemical and hydrological investigations. Because of the potentially high rates of advance possible using mechanical excavators, existing geologic features, such as major faults, can be intersected and examined much earlier in the characterization period. The welded tuff formations and other lithogolic units present at the proposed repository site have properties that are believed to be highly conducive to efficient application of various mechanical excavators, including tunnel, raise and shaft boring machines.

This paper is a snapshot of an active, large research program at the Colorado School of Mines (CSM). The work itself encompasses the gamut of experiments from small-scale material properties tests to large-scale mechanical boring tests. It is not possible to capture all facets of the program in this paper, so emphasis is given to preliminary estimates of mechanical excavators. The remainder of this paper will first provide an overview of the phases of the project, and subsequently focus on the results of the performance calculations for mechanical excavators. Most of the preliminary results pertain to the Tunnel Boring Machine (TBM). Features of other mechanical excavators will be described and their relative performance in terms of advance rate and cost per unit excavation will be given. In keeping with the industry standard, all units are conventional English units and conversion to SI units is not made in the text.

DESCRIPTION OF WORK

The primary objective of this research program is to assess the performance of various types of mechanical excavators that can be employed in the construction of ramps, shafts, raises and drifts for site characterization and potential repository construction. In addition, this program will develop initial guidelines to enhance design and performance of excavation systems, including the machinery and the back-up unit. It will also provide information for the excavation support systems, including the roof support, muck haulage, and ventilation. Thus, a total system approach will be followed in the design optimization and performance evaluation of various mechanical excavation equipment. These goals will be addressed through a four-phase research effort currently in progress as described below:

Phase 1: During this phase, CSM is conducting a detailed assessment of TBM performance for driving ramps, main entries, haulageways, emplacement drifts and other excavations considered suitable for TBM application in site characterization and repository construction. Various computer models developed by CSM from previous mechanical excavation research programs are used for machine performance predictions. The predictions are based on the available physical property and geologic information complemented with results from a series of laboratory tests, section petrographic analyses. The machine performance predictions considered the following parameters relevant to TBM application: (1) cutter type, geometry and spacing; (2) cutterhead shape and cutter layout; (3) machine thrust, torque and power requirements; (4) cutter consumption and costs; (5) back-up system requirements; (6) material haulage and roof support systems; (7) special machine features; (8) capability to drive declines, make turnouts from existing entries and bore through intersections; and (9) overall machine advance rates and construction costs. The main emphasis is on the potential repository horizon material, but estimates also consider other lithological units likely to be encountered in the construction of ramps and shafts. In addition, performances of other types of mechanical excavators, including roadheaders, Mobile Miners, raise drills and shaft borers are being evaluated.

Phase 2: This phase includes an extensive series of laboratory linear cutting tests to develop actual mechanical cutability data in welded tuff samples obtained from outcrops of the proposed repository material. These tests are being conducted with candidate cutter types at spacings, penetrations, and thrust loads typically encountered in mechanical boring of rock formations similar to Yucca Mountain lithologies. The data are being analyzed to develop more accurate and reliable estimates of excavator requirements and specifications in terms of thrust, torque, power, rate of penetration and cost of bits. The test results are also being used to develop guidelines for the optimum design of the various excavation systems.

Phase 3: This phase, potentially starting in early 1991, will conduct a series of laboratory-scale excavator tests using CSM's 6 ft. diameter boring machine. Tests will be performed on a sample of welded tuff using a cutterhead dressed with state-of-the-art disc roller cutters. Tests will include boring horizontally and in the vertically down position to simulate the operation of tunnel and shaft boring machinery. Tests will be conducted under dry and wet cutting conditions to assess the effectiveness of muck removal, dust suppression and potential water infusion into excavation walls. All boring parameters, including machine thrust, torque, cutterhead power, rate of penetration, specific energy, and bit wear will be measured and evaluated. The muck generated from each test will be collected to evaluate the system and power requirements for bottom-hole cleaning and hoisting in mechanical boring of repository shafts.

Another objective of this phase is to assess geologic mappability of bored openings. After completion of the bore, researchers will examine the excavation walls visually using conventional geologic mapping techniques and also by using stereo-photographic techniques to assess fracture and joint mappability. This will provide information on which to base a preliminary assessment of the geologic mappability of machine excavated openings for site characterization studies.

Phase 4: In this phase, a review and assessment of the new and emerging mechanical excavation technologies is being conducted for potential application to repository construction. This review includes new and anticipated developments in tunnel, raise and shaft boring machines, roadheaders, Mobile Miners, as well as emerging technologies in muck removal and disposal, roof support, ventilation and dust suppression, machine back-up systems, ground probing and machine automation.

MACHINE PERFORMANCE IN THE PROPOSED REPOSITORY HORIZON

The quality of the estimation of mechanical excavator performance depends on the quality of the input parameters. The stratigraphic section at Yucca Mountain comprises a wide range of mechanical properties from the weak non-welded Paintbrush Tuff near the surface to the very strong nonlithophysal tuff at the potential repository horizon. The estimates of machine performance concentrate on the Topopah Spring welded unit (TSw2) for which some published material properties are available.[1,2] It is clear that the sparsity of material properties renders the initial predictions tenuous. However, the requisite rock properties being generated in Phase 1 of this project will enhance these preliminary estimates.

As part of Phase 1 research effort, preliminary machine performance estimates were developed for various types of mechanical excavators in the repository horizon. The mechanical excavation equipment evaluated include TBMs, roadheaders, Mobile Miners, shaft boring machines and raise drills. Equipment sizes were selected based on the conceptual design options for the Exploratory Shaft Facility (ESF) and the repository.[3] The excavation and machine dimensions used in the machine performance calculations were as follows:

1. Tunnel Boring Machine: Circular drifts of 25 ft. in diameter.

2. Mobile Miners: Rectangular drifts of two sizes--22 ft. by 14 ft. and 30.5 ft. by 16 ft.

3. Roadheader: horseshoe-shaped drifts 22 ft. wide by 12.5 ft. high.

4. Shaft Boring Machine: 16 ft. diameter (opening size before lining).

5. Blind Shaft Borer: 16 ft. diameter (opening size before lining).

6. V-Mole: 16 ft. diameter (opening size before lining).

7. Raise drills: two sizes, 6 ft. and 16 ft. (the 6 ft. raise is to serve as the pilot hole for the 16 ft. diameter V-Mole.

Performance of these various mechanical excavators has been evaluated using rock properties available in the literature as well as mechanical results concurrently generated for this study. The performance calculations for each machine type have been completed but page restrictions prevent a presentation of all of the calculational methodologies and results here. Specific examples of quantitative results will be given for the performance of TBMs. Extensive results pertaining to other mechanical excavators will be forthcoming in technical reports.

Tunnel Boring Machines

Performance predictions are developed for a standard and high-power TBM. The standard machine is equipped with 17 in. disc cutters rated at 50,000 lb. average load. The high-power machine uses newly developed 19 in. diameter disc cutters with a load rating of 65,000 lbs. In addition, the high power TBM has a slightly higher cutterhead rotational speed.

The results of the performance estimates for the two machines are summarized in Table 1 along with the machine thrust, torque and power requirements. Also included are the cutter cost estimates per cubic yard of material excavated. As expected, the high power TBM provides for higher rates of penetration with a longer cutter life, hence lower cutter costs.

TABLE 1 PERFORMANCE ESTIMATES FOR THE TBM IN THE REPOSITORY HORIZON WELDED TUFF (TSw2)

SPECIFICATIONS	STANDARD TBM	HIGH POWER TBM
Cutterhead Diameter	25 ft	25 ft
Rotational Speed	6.36 rpm	7.0 rpm
Cutters	50 @ 17 in. diameter	47 @ 19 in. diameter
Max. Cutter Load	50,000 lbf	65,000 lbf
Cutterhead Power	6 @ 400 hp	7 @ 450 hp
Max. Operating Torque	1982 x 10^3 ft-lbf	2026 x 10^3 ft-lbf
Operating Thrust	2500 x 10^3 lbf	2820 x 10^3 lbf
Penetration per Revolution	0.18 in	0.25 in
Penetration Rate	5.72 ft/hr	8.75 ft/hr
Cutter Life	66 hrs	73 hrs
Tunnel Length per Cutter	376 ft	637 ft
Approx. Cutter Costs	5.41 \$/yd^3	5.15 \$/yd^3

To estimate the daily advance rate, an estimate of machine utilization is made. In general, TBM utilization is influenced by: tunnel grade, haulage method, water inflow rate, rock quality, tunnel curves, and crew training and motivation. We have considered these parameters in the calculations of advance rate. Assignments of shapes, curves and back-up systems were arbitrary to capture a range of possible advance rates. Estimating utilization involves a great deal of judgement and past field experience.

Table 2 lists the parameter variations, approximated utilization factors and the resultant daily advance rates for the standard and the high power TBMs operating in the repository horizon material. As expected, best performance is achieved when the tunnel is nearly horizontal and either rail haulage or conveyor systems are used for muck removal.

TABLE 2 - PROJECTED ADVANCE RATES FOR TBMs IN THE REPOSITORY HORIZON MATERIAL (TSw2)

STANDARD TBM:

Slope %	Curve Radius (ft)	Backup System	Penetra. Rate (ft/hr)	Utiliz. %	Advance Rate (ft/day)
-1 to +3	none	rail	5.7	55	75
-1 to +3	none	conveyor	5.7	50	68
-8.9	none	conveyor	4.7	45	51
-14	none	conveyor	4.2	40	40
-21	none	conveyor	4.0	35	34
-1 to +3	600	rail	3.5	35	29
-8.9 to -21	600	conveyor	3.2	30	23

HIGH POWER TBM

Slope %	Curve Radius (ft)	Backup System	Penetra. Rate (ft/hr)	Utiliz. %	Advance Rate (ft/day)
-1 to +3	none	rail	8.8	55	116
-1 to +3	none	conveyor	8.8	50	106
-8.9	none	conveyor	7.5	45	81
-14	none	conveyor	7.0	40	67
-21	none	conveyor	6.8	35	57
-1 to +3	600	rail	5.0	35	42
-8.9 to -21	600	conveyor	5.0	30	36

The Mobile Miner

The Mobile Miner is a relatively new mechanical excavation concept developed primarily for mining applications. It excavates the rock with a thin rotating wheel dressed with peripherally mounted disc cutters. In operation, the wheel sweeps across the face from one side to another as it rotates in a vertical plane, creating a rectangular opening with arched ribs. The opening height is determined by the wheel diameter while the width is controlled by the angle of swing. The Mobile Miner is not designed to compete with TBMs in terms of production rate in long, relatively straight entries. It is rather intended as a mobile hard rock machine with high operational flexibility. From the repository perspective, the Mobile Miner can be used to excavate alcoves and short drifts. A new design variation includes a ranging wheel which produces a horseshoe shaped cross-section. Other variations include double ranging drums to enlarge existing openings.

The attainable penetration rates (2.8-3.5 ft/hr.) for the Mobile Miner are much less than for either TBM. The cutter costs ($7.80-$8.50/yd^3) for the Mobile Miner are higher due to lower system rigidity and the cyclic contact of the cutters with the rock.

Roadheaders

Roadheaders provide a flexible and versatile excavation system although their economical use is limited to rock formations with a compressive strength of less than 15,000 psi. Stronger formations can be excavated with roadheaders if they contain a sufficiently dense fracture network so that the machine can rip blocks off the face. Again, being partial face machines, the roadheaders are not capable of matching the production capacity of TBMs, but their high mobility and the ability to create openings of practically any shape and size make them very attractive for many aspects of underground construction.

After consideration of the potentially very high compressive strength and abrasivity of the repository horizon welded tuff, a heavy-duty roadheader was selected for performance calculations. The roadheader selected was a 100 ton machine equipped with a 400 hp. cutterboom. As expected, the cutter costs ($12.50/yd^3) for the roadheader are higher than either the TBMs or the Mobile Miner. Hard, abrasive materials such as welded tuffs, cause excessive wear on the drag-type bits which the roadheaders use. Despite the relatively high bit costs however, the roadheaders offer key attributes of mobility, versatility and the ability to excavate openings of various sizes and shapes.

Blind Shaft Borer

Several options are available for the mechanical excavation of the repository shafts. If the underground access exists, the shafts can be raise drilled or reamed from an initial pilot hole constructed by raise drilling. Without prior access to underground, shafts have to be excavated blind using full- or partial-face machines and some form of muck removal system. Drilling of shafts from surface-mounted rigs is not considered suitable for the repository application because considerable quantities of fluids for bottom-hole cleaning and cuttings transport to surface are required.

The blind shaft borer (BSB) in this analysis can be considered a double-ended TBM turned on one end. It operates very much like a TBM in terms of rock penetration and the design of the gripping system. The muck collection and removal from the hole bottom is accomplished using a mechanical pick up system. It is believed that in the Yucca Mountain lithologies, the overall performance of the blind shaft boring will be governed primarily by the shaft support systems rather than by the machine's attainable penetration rate as a function of the geology and the rock conditions.

For the blind shaft borer, performance estimates were developed for a low and a high-speed machine 16 ft. in diameter. The cutter costs are lower

($6.08 versus $8.07/yd^3) for the low-speed machine since the cutters are loaded to near capacity and penetrate deeper during each revolution of the cutterhead. This means a shorter distance travelled per cutter per foot of shaft excavated and the cutter wear is primarily a function of distance travelled.

Taking into account the hoisting and the shaft lining requirements, the BSB utilization in the repository environment is expected to average 30 percent. With this utilization factor, the estimated daily advance of the BSB is about 40 ft. This would allow for pouring of two, 20 ft. concrete lining rings per 24-hour period.

Vertical Wheel Shaft Boring Machine

The vertical wheel shaft boring machine (SBM) is a relatively new concept for the mechanical excavation of shafts in rock. The basic principle of operation is very similar to the Mobile Miner where the rock is broken by a rotating thin cutterwheel dressed with peripherally-mounted disc cutters. For the SBM, the cutterwheel assembly is rotated about the shaft axis and thrusted downward, in addition to being rotated about its own horizontal axis. A dozer-type blade follows the cutterwheel and scrapes the cuttings into a pile which is in turn picked-up by a clamshell bucket for transfer into a hoist for transport to the surface.

Being a part-face machine, the estimated instantaneous rate of penetration of the SBM is lower than the BSM, 4.2 versus 6.0 ft/hr, respectively. However, especially for site characterization studies, the SBM may offer a significant advantage over the BSM because it allows for much easier access to the shaft bottom.

Since the SBM is a new design concept, no field data exist as yet to estimate its expected utilization. It is anticipated, however, that its utilization will be close to that for the BSM at around 30 percent which gives a daily advance rate of 30 ft. This rate again assumes that the shaft is lined directly behind the machine as the boring operation proceeds.

Raise Drills

As noted previously, the repository shafts can be excavated by raise boring techniques once underground access is established. In that case, raise drilling is usually the fastest and the most cost effective means to construct shafts. Shaft construction by raise drilling is a two-step process. First, a pilot hole is drilled in the desired location. A reamer is then attached to the drill pipe to enlarge the hole to its final diameter. Shafts up to 20 ft. in diameter have been successfully constructed using raise drilling techniques.

For the purposes of this study, performance predictions were developed for two raise sizes, 6 and 16 ft. The smaller raise is intended to serve as the pilot hole for the V-mole. The estimated penetration rates for the 6 and 16 ft. raise drills are 8.1 and 2.3 ft./hr., respectively in TSw2. As expected, the cutter costs for both raises are much higher than for TBMs, ranging from \$17.40 to \$18.50/yd^3.

The utilization factors for the 16- and the 6-ft. raise drills were estimated at 60 and 55 percent, respectively. The lower utilization of the smaller machine was due to faster penetration rate and the relatively longer time to change drill pipes. With these utilization factors, the estimated daily advance for the 16 ft. raise is about 33 ft. while the smaller drill is expected to achieve a daily advance rate of close to 100 ft. It is believed that a highly-trained crew can increase the machine utilization to over 70 percent, meaning even higher rates of advance for both drills.

The V-Mole

The V-Mole is similar in principle to the blind shaft borer except that it uses a predrilled pilot hole for muck disposal, thus requiring previously developed underground access. A 16 ft. diameter V-Mole needs about a 6 ft. pilot hole to handle effectively the quantities of muck generated during the excavation process. The machine utilizes a V-profile cutterhead so that the gravity forces the cuttings into the pilot hole and down to the haulage level for transport to surface. The pilot hole can also be used for machine guidance to achieve strict verticality to allow proper hoist installation and operation.

Performance in the repository horizon was predicted for a standard V-Mole and an upgraded version. The upgraded unit uses larger cutters and incorporates a higher-speed cutterhead and more power. It is also fitted with a dome-shaped cutterhead to assist in steering and to distribute the cutter forces more uniformly. The dome shape is also designed to improve steerability and to avoid unwanted direction changes due to deviations in the pilot hole.

The utilization of the V-Mole is influenced by the same factors discussed earlier for the SBM and the BSB. Including shaft lining considerations, it is estimated that a daily advance rate of about 40 ft. can be attained with the V-mole in the repository horizon material. In addition to this excavation rate, project scheduling would need to take into account the time required to drill the 6 ft. diameter pilot hole.

OTHER CONSIDERATIONS

Performance predictions were also developed for a 25-ft. diameter standard and a high-power TBM in other lithological units of the repository. In the weaker formations, penetration rates exceeding 26 ft./hr. are estimated to be feasible with a high-power TBM. This rate is at or near the muck removal capacity for a 25 ft. machine bored tunnel with the present-day muck removal technology.

As discussed earlier in the description of work, a concurrent research activity in Phase 2 includes an extensive series of laboratory linear cutting tests designed to provide actual cutting data to enable more accurate and reliable predictions of the mechanical excavation performance for the proposed repository.

The laboratory cutting tests were conducted on the CSM linear cutting machine using different geometry drag bits and disc roller cutters. Various combinations of cut spacings and bit penetrations were tested in samples of welded tuff collected from Fran Ridge outcrops of TSw2. Test results include the measured average and peak cutting forces, the ratios of cutter forces and the specific energy of cutting. These results are currently being analyzed and evaluated to develop more accurate performance estimates for the excavation machinery discussed in this text.

CONCLUSIONS

This research program is designed to provide timely evaluation of the performance of mechanical excavators for site characterization and possible construction of the Yucca Mountain nuclear waste repository. The machine performance estimates calculated to date have shown that the rock formations likely to be encountered during the construction of the repository have properties highly conducive to cost effective application of various types of mechanical excavation systems, including tunnel boring machines, Mobile Miners, raise drills and shaft boring machines.

The resulting information from this ongoing research program will be used to (1) develop machine specifications for construction of ramps, entries, haulageways, panel drifts, shafts and raises; (2) enable optimal design and operation of various types of mechanical excavators; and (3) provide accurate predictions of machine performance in Yucca Mountain lithologies.

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