Technical Paper

U.S. ARMY CORPS OF ENGINEERS **BUILDING STRONG®**

Preliminary Analysis of Potential Vibration Impact to Old Hickory Lock & Dam from Proposed Quarry Operations

Old Hickory Lock and Dam, located approximately 25 miles upstream from Nashville, Tennessee, was authorized for construction by the Flood Control Act of 1938, and the Rivers and Harbors Act of 1946. It is a "run-of-the-river," multi-purpose project that provides hydroelectric power, navigation, environmental stewardship and recreation. It is a combination of concrete gravity sections and earth embankment.

The U.S. Army Corps of Engineers Nashville District has conducted an initial investigation to assess the impacts quarry blasting will have on both the concrete structures and the embankment. The analyses show the quarry can be operated without impact to the dam. To ensure that safe thresholds referred to below are met, the District recommends the implementation of a jointly monitored test blast program with the quarry to confirm parameters. We also recommend a permanent vibration monitoring system to ensure compliance with criteria for the life of the quarry. The Corps requires these measures at its own construction projects when blasting near existing dam structures.

Concrete Structures

We have no concern regarding the safety of the concrete structures. The seismic analysis for Old Hickory dam concluded the concrete structures have a low susceptibility to damage from the maximum probable earthquake (MPE), which is estimated to have an acceleration of 0.14g at the dam. An earthquake of this magnitude would subject the concrete structures to much greater vibrations than expected from quarry blasting. The calculated vibrations at the concrete structures that would be caused by quarry blasting are well below thresholds of concern.

Embankment

Our analyses show that the embankment will be stable and not fail due to quarry blasting. Given the signifiant public concern expressed regarding the safety of the dam as a result of vibrations from quarry blasting, the Corps has taken a very conservative approach in its investigation of possible dam safety issues. Our analyses focused on the portion of the embankment nearest the quarry boundary. In this reach there are some loose sands of varying thickness in the foundation that might be a concern during an earthquake from the standpoint of liquefaction and loss of strength.

For the embankment, vibrations can induce several failure modes. These include slope failures caused by large ground motions, slope failures due to liquefaction of foundation soils, and deformation of the dam crest and loss of freeboard due to liquefaction of foundation soils. When evaluating the impacts of vibration on the soil, peak particle velocity (ppv) is the unit of measurement. The calculations discussed below use ppv measured in inches per second (in/sec).

Regarding slope failures due to large ground motions, it should be noted that embankment dams have very low natural frequencies and are not particularly susceptible to damage due to blast vibrations which have much shorter durations and much higher frequencies than an earthquake. Based on the 1983 Old Hickory Seismic Study, the calculated acceleration expected at the project from the maximum probable earthquake is 0.14g. Based on correlations from the United States Geological Survey this would be described as a level VI earthquake with perceived shaking to be strong but the potential for damage light. Estimated peak particle velocities would be on the order of 3 to 6 in/sec. These are higher than anything the quarry operations would generate.

Regarding possible failure related to liquefaction of the foundation sands, the Corps calculated peak particle velocities anticipated due to quarry blasting. We also performed a screening analysis adapted from seismic stability procedures to determine the susceptibility of the foundation sands to liquefy from vibrations. We then assessed the impact on the embankment stability using reduced residual strengths of the foundation sands.

Generally, a ppv of 1.0 in/sec is an accepted conservative threshold value when considering blasting near earth embankments. For liquefaction concerns, the Bureau of Reclamation (Charlie 1985) recommended the following:

"If blasting is required, peak particle velocity and pore-water pressure should be monitored and evaluated at several locations in the dam, foundation soils, and abutment. Peak particle velocities should be kept below 2.5 cm/sec [1 in/sec]."

Studies of field behavior of full-scale earthfill and tailing dams subjected to blast vibrations indicate that ppv's of1.0 in/sec, 2.0 in/sec, and 3.9 in/sec are reasonable thresholds to minimize pore pressure buildup in dams constructed of or on soils sensitive, moderately sensitive, and not sensitive to vibration, respectively (Charlie 1985, 2000; Charlie et al. 2001). Moreover, ppv's up to 2.76 in/sec have been found to yield little to no residual pore pressures, less than a tenth of what would be required to initiate liquefaction, which is in agreement with a USSR study (Puchkov 1962) and reports of the same (Charlie et al. 2013). Consequently, the proposed thresholds above 1.0 in/sec, 2.0 in/sec, and 3.9 in/sec can be considered conservative provided that, if any observed residual pore pressures occur, they are allowed to dissipate prior to the next blast. Given typical quarry operations, where days may occur between blasts, it is unlikely pore pressures, even if impacted, would not dissipate between blasts. In any case we have automated instruments in the foundation that provide data in real time to monitor pore pressures. These will tell us if blasting impacts the pressures and facilitate field adjustments in the quarry's operation. Blasting can only be done during the week and during daylight hours so we will be able to monitor and evaluate readings in real time for every blast.

Though likely distances from locations in the embankment underlain by loose sands to the closest quarry operation are 750 feet or more, the Corps assumed conservative distances of 600 feet from the nearest quarry boundary to the very left end of the embankment for its calculations to determine peak particle velocity. The calculated peak particle velocity at the embankment at this conservative distance is 1.25 in/sec. For the more reasonable distances mentioned above, the calculated ppv's drop below the 1 in/sec threshold.

The ppv results notwithstanding, we performed an analysis to determine the effect on the shear strength of the foundation sands as if they were subjected to an earthquake with large vibrations and excessive strains. This results in the lowest expected residual shear strengths for use in stability analyses. The results of these show the embankment remains stable and factors of safety met.

Regardless of the above analyses, the Corps has given several recommendations to the quarry owners necessary to satisfy our core commitment to dam safety and ensure thresholds are not exceeded. The quarry developers agreed to a jointly monitored test blast program which will give site specific values for determining blast vibrations and allow the setting of safe blasting parameters to ensure no harm to the embankment. This will allow adjustments to such things as decreasing the charge weight per delay and increasing the buffer distance between blasting and the dam. They also agreed to install permanent vibration monitoring instruments to monitor the dam for the life of the quarry, ensuring that safe thresholds are monitored for compliance.

Concerns have also been expressed regarding air blasts, dust control, and flyrock. Regulatory requirements enforced by the State and the Mine Safety Health Administration dictate the quarry must provide for both on-site worker safety as well as for those of surrounding property owners.

Airblast Vibrations
Tennessee state requirements limit noise levels to a maximum of 140 dB. Just as with the ground vibrations, airblast vibrations will have to be determined in a test blast program with blast thresholds designed to be protective of nearby structures and people through continuous real-time monitoring during regular quarry operations.

Flyrock
The potential for flyrock and proposed methods to prevent it will have to be addressed as required by the state code and measures can be taken to address this as a hazard to the public at the nearby Corps recreation beach area as well as to boaters in close proximity. Flyrock will be most problematic during the early stages of development and mining because blasting will be nearer the surface. Properly designed blasts and cover matting over blast areas should address this. This problem will be somewhat mitigated once blasting is lower down in the excavated pit.

Estimated Vibration Calculations
When evaluating vibration impacts, it is the peak particle velocity (ppv) in inches per second that is used. The Corps made various calculations using the industry accepted method scaled distance approach. This is the same method specified for our Kentucky Lock project blasting in order to protect the adjacent lock and dam from damage. Those results are in Tables 1 and 2 below.

The equation for ppv is based on the size of charge, distance from the blast, and factors related to site conditions.

> ppv = k(D/Wm)-β
> D is the distance to the point of concern
> W is the charge weight per delay
> k is a ground transmission or attenuation factor
> m and β are empirical site constants.

For quarry blasting, characterized by row or line charges, m, β, and k are chosen as 0.5, 1.82, and 182, respectively as cited in the ISEE Blasters Handbook. For sensitive structures located in close proximity to the blasting, it may be appropriate to adopt more restrictive values for k and β. For these, k = 242 and β = 1.6, were used as recommended in the ISEE Blasters Handbook, to represent a general construction scenario with an upper bound on the confidence level.
We then calculated ppv's for various distances from the blasting area while varying the charge weight per delay, k and β, as shown below in Tables 1 and 2 below.

TABLE 1

k = 182, β = 1.82		Peak Particle Velocity, inches/sec							
		Distance, ft							
		250	500	600	750	1000	2000	3000	3500
Charge Weight per delay, lbs	100	0.52	0.15	0.11	0.07	0.04	0.01	0.006	0.004
	150	0.75	0.21	0.15	0.10	0.06	0.02	0.008	0.006
	200	0.98	0.28	0.20	0.13	0.08	0.02	0.011	0.008
	250	1.20	0.34	0.24	0.16	0.10	0.03	0.013	0.010
	300	1.41	0.40	0.29	0.19	0.11	0.03	0.015	0.012
	350	1.63	0.46	0.33	0.22	0.13	0.04	0.018	0.013
	400	1.84	0.52	0.37	0.25	0.15	0.04	0.020	0.015
	450	2.04	0.58	0.42	0.28	0.16	0.05	0.022	0.017
	500	2.25	0.64	0.46	0.30	0.18	0.05	0.024	0.018
	1000	4.22	1.20	0.86	0.57	0.34	0.10	0.046	0.035

TABLE 2

k = 242, β = 1.6		Peak Particle Velocity, inches/sec							
		Distance, ft							
		250	500	600	750	1000	2000	3000	3500
Charge Weight per delay, lbs	100	1.40	0.46	0.35	0.24	0.15	0.05	0.026	0.021
	150	1.94	0.64	0.48	0.33	0.21	0.07	0.036	0.028
	200	2.44	0.81	0.60	0.42	0.27	0.09	0.046	0.036
	250	2.92	0.96	0.72	0.50	0.32	0.10	0.055	0.043
	300	3.38	1.11	0.83	0.58	0.37	0.12	0.063	0.050
	350	3.82	1.26	0.94	0.66	0.42	0.14	0.072	0.056
	400	4.25	1.40	1.05	0.73	0.46	0.15	0.080	0.062
	450	4.67	1.54	1.15	0.81	0.51	0.17	0.088	0.069
	500	5.08	1.68	1.25	0.88	0.55	0.18	0.095	0.075
	1000	8.85	2.92	2.18	1.53	0.96	0.32	0.166	0.130

The distance from the nearest quarry property boundary, which is a conservative assumption for the blast location, to the left-most end of the Old Hickory Dam embankment is about 600 feet; to the nearest lock wall is about 3000 feet; and to the powerhouse is about 3,500 feet. Assuming a charge weight per delay of 500 lbs., which is described by APC as a production charge - or a "…heavy AN/FO explosives product charge…", the resulting ppv's are highlighted in Tables 1 and 2 above and summarized in Table 3.

TABLE 3

Old Hickory Dam Feature	Distance from quarry boundary to feature	Peak Particle Velocity, in/sec*	
Left-most embankment	600 ft.	0.46	1.25
Nearest lock wall	3000 ft.	0.024	0.095
Powerhouse	3500 ft.	0.018	0.075

For the concrete structures like the lock wall and powerhouse, the generally recognized threshold above which concern for damage to structures due to vibrations becomes a consideration is 2 in/sec. For comparison purposes, during the blasting adjacent to Kentucky Lock and Dam the following maximum allowed ppv's were specified in order to protect the structures at Kentucky Lock:

KY Lock Feature	Peak Particle Velocity in/sec, during production
Nearest lock wall and U/S cofferdam	4
Lock Control Building	2
Transmission Towers	4
Switchyard	2

The calculated values in Table 3 for the concrete structures are between 1 and 2 orders of magnitude less than the thresholds.