An Innovative Approach of Vibration Testing of Concrete Structures Using Performance Based Evaluation Techniques

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ABSTRACT

Many of the current state of the art structural health monitoring (SHM) techniques are reliant on ambient excitation to determine the modal behavior of a structure. Common sources of ambient excitation are wind, water flow through dams, traffic on bridges, or seismic activity. However, it is possible for none of these sources of ambient excitation to be available for a structure. For example, dams can have strict limits on how much water can be released over certain time periods and may not allow traffic on them. In these cases, it can be necessary to induce modal excitations from other sources such as mechanical shakers or a cold gas thruster (CGT). Mechanical shakers allow specific modes to be activated but are heavy and require space that may not be available on all structures. The U.S. Army Corp of Engineers (USACE) has many large concrete dams that require such excitation to obtain modal information. This information may then be used to directly obtain changes in fixity or to calibrate finite element models of the structure.

To determine the limits of the CGT for characterizing a structure, a reinforced concrete test structure was subject to the CGT pulse force in several locations with 8 accelerometers recording the motion of the structure. Using results from this effort, a shock response spectrum can then be used to compare a model's behavior to that of the structure itself and to validate or match a model. Additionally, knowledge of a structure's dynamic behavior in both an intact state and a damaged state can directly identify a change in boundary conditions, indicating separation of monoliths or foundation sliding

The reinforced concrete test structure was used to test the CGT, as well as to establish the methods used to match the finite element analysis (FEA) models to a physical test. A small CGT was used to accelerate the structure in several configurations, which included changing the location and direction of the load. The Shock Response Spectrum (SRS) is used to compare the response of the structure to both different loads and to the modeled behavior of an FEA model built in LS-Dyna.

The material attributes of the concrete and soil beneath the slab are unknown, but the LS-Dyna model matches closely to the physical tests. Peaks in the SRS can indicate modal frequencies, while double peaks in a symmetric structure can indicate some asymmetry, either from additional mass, or more likely, from reductions in stiffness. The addition of mass or reduction in stiffness may be added to the model to determine exactly how or where damage has occurred. This will discuss how the models are matched to the structure using the shock response spectrum and how damage may be indicated by shifts in the shock response spectrum, as well as the appropriate structures for this application.

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INTRODUCTION

Numerical modeling and analysis tools have become the primary source of information for evaluating how dams behave, but a small number of failure events and a scarcity of physical tests reaching nonlinear behavior make validating these models challenging. Determining the behavior of these structures up to the point that nonlinearity begins is an important first step in identifying the onset of failure, these techniques can also determine a change in boundary conditions. This work applies Performance Based Testing (PBT) procedures to obtain fundamental characteristics of a structure by inducing impulse loading into the structure with use of a Cold Gas Thruster (CGT). The CGT uses pressurized gas to induce a load of short duration. The structural responses are captured with accelerometers located at key positions on the structure [1].

In the past vibration data has been limited to ambient sources due to the cost and the magnitude of force required to accelerate civil structures. One downside to ambient testing is the limitations of modal frequencies activated. Dams also lack traffic, the main source of ambient vibration on bridges. Forced vibration tests can deliver excitations of larger magnitudes, enabling activation of a broader range of modal frequencies. Environmental factors can also more easily skew the measured results with ambient vibrations due to wind, pumps, or other constant excitation.

Mechanical shakers can be used to induce forced vibrations, these shakers require a large space to work, precluding their use on structures without the necessary space. When such is the case, ambient vibrations are the only source of excitation available [2]. The CGT is a small and lightweight tool that can easily be mounted on the ground or wall of a structure, allowing forced vibrations to be introduced to any dam with fewer limitations to the location.

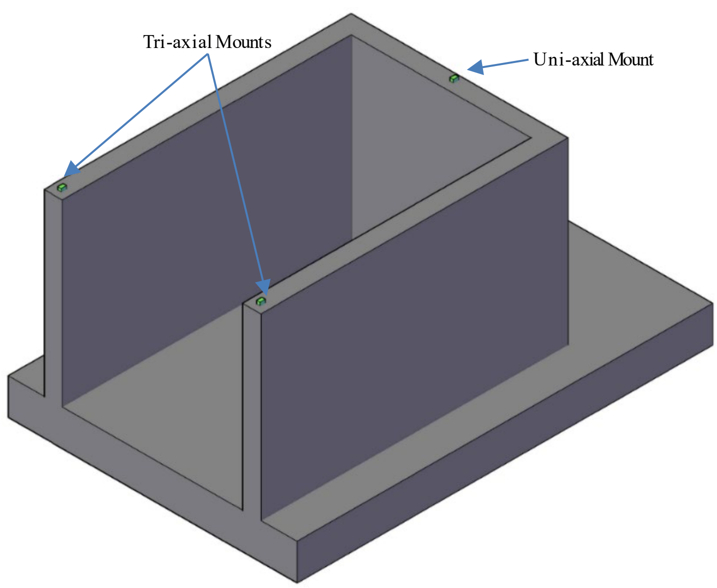

Figure 1. Accelerometer Layout

METHODOLOGY

A small concrete reactions structure was used demonstrate the effects of the CGT. The back wall has a width of 12 ft and the two side walls have a length of 16 ft, all the walls have a height of 10 ft and a thickness of 1 ft., they are supported by a 2 ft. thick slab in turn supported by piles.

Measurement Layout

For each CGT pulse, 9 channels were used for recording data. Each of these channels recorded at a frequency of 10,000 Hz. There were 8 QA-650 accelerometers used to record acceleration responses on the structure. The test site is far from traffic or other sources of ambient excitation, so all movement of the test structure that is large enough to be detected by the accelerometers is due to the CGT. Two triaxle mounts and one single axis mount used to record the behavioral responses on the structure. A load cell and accelerometer were also placed on the CGT mount to record the impulse load and acceleration. The position of each accelerometer was determined using pre-experimental numerical models and is shown in Figure 1, on the top of corners of the left and right wall and on the top center of the back wall.

COLD GAS THRUSTER

PBT methods with the use of the CGT allows for dam owners and operators to obtain vibration data for the development of numerical models. However, the data may also be used directly, the indication of two similar natural frequencies may represent an asymmetry in a structure that may show a change in boundary conditions or loss of mass on one side [3].

The CGT was attached to the structure at 5 locations, on the bottom slab, the back wall pointing both to the side and upward, and on one side wall pointed both sideways and upward. At each location, 3 impulse loads were induced, the average responses at each location are shown on Table I. The CGT consists of a cylindrical chamber with a thin metal diaphragm sandwiched between converging and diverging nozzles. The chamber is pressurized with an inert gas, and when the diaphragm reaches its maximum stress level, it ruptures abruptly, delivering a concentrated force pulse. An aluminum 0.032 in. thick diaphragm was used throughout to produce a pulse of about 3.5 kip.

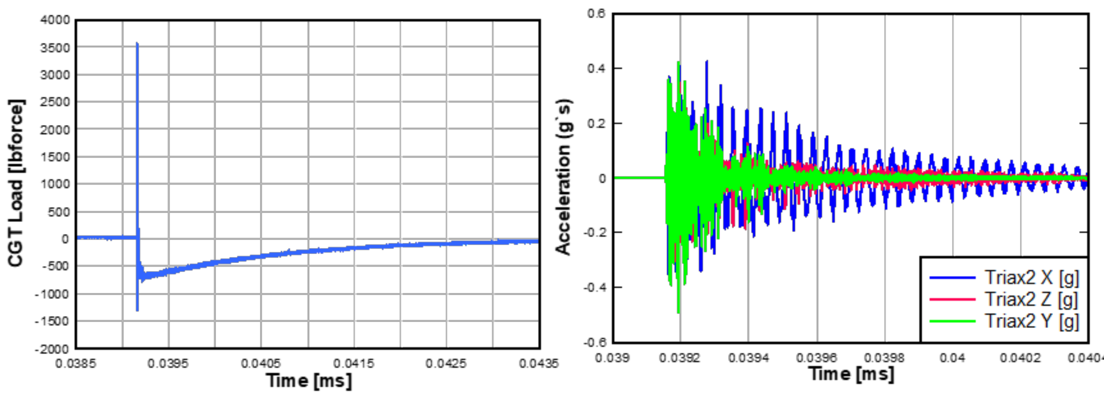

Figure 2. (**a**) CGT force pulse measurements for Experiment 2; (**b**) Acceleration response measurements from triaxial mount 2

ANALYSIS OF TEST RESULTS

A total of 15 CGT tests were conducted during this study. For each test, 7 acceleration measurements were taken from the accelerometers that were mounted on the top of the left and right wall of the reaction structure and also the back wall measuring along a single axis. When processing the data for each CGT shot, it is apparent that the global responses were independent of the location the CGT. Even though the pulse loads recorded for each shot showed slight variations in peak magnitudes and the thruster was set in five configurations, the shock response spectrums (SRS) displayed near identical performance. What did change with the SRS, were the magnitudes of total activity across the spectrum. The relative activation of modes remained approximately constant. What is critical with the CGT testing is that the pulse load is large and fast enough to activate all the important modal frequencies of the structure. The location of the CGT is flexible, but it must be placed at a point that deflects in the direction of the CGT in to any of the pertinent modes.

Table I. ACCELERATION AVERAGES FOR EACH CGT LOCATION.

Acceleration Averages for each CGT Location							
		Triaxial Mount 1		**Triaxial Mount 2**		**Single Mount**	
CGT Location #	**X1**	**Y1**	**Z1**	**X2**	**Y2**	**Z3**	**X3**
1	1.08	0.87	0.79	0.52	0.45	0.45	0.25
2	1.33	1.63	0.82	1.53	1.57	1.03	0.74
3	0.50	1.19	0.73	0.62	1.33	0.55	1.18
4	0.30	0.78	0.65	0.63	0.66	0.29	0.60
5	0.50	1.30	0.96	0.59	0.72	0.41	0.62

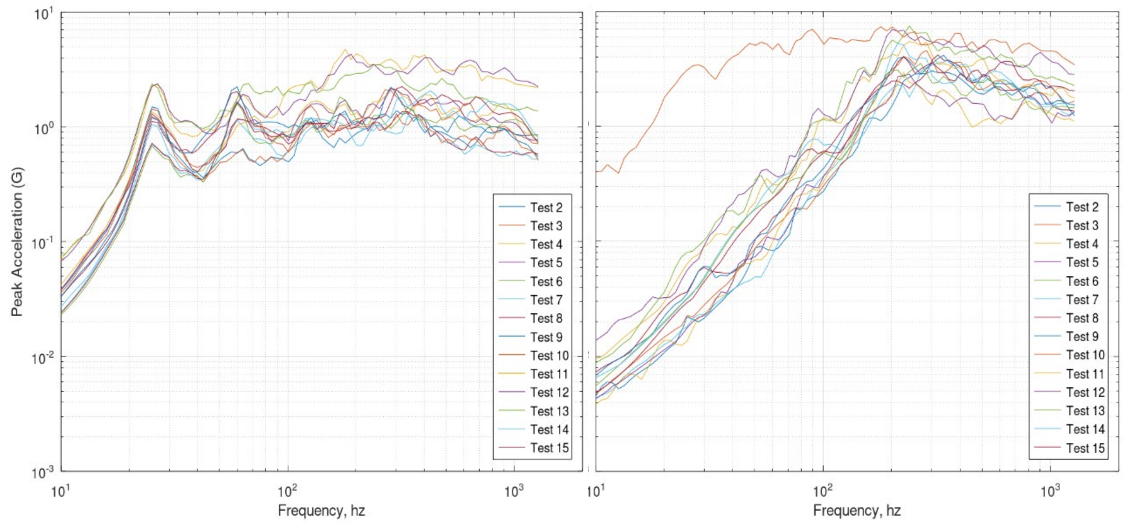

Figure 3. Shock Response Spectrum Triax Point 2, X Direction

Shock Response Spectrums

The SRS was chosen as the main tool for evaluating the CGT effects since they are an excellent way to compare modal behavior induced by impact loads. SRS methods are primarily used within the aerospace industry but these methods are a valuable tool with regard to earthquake engineering. This method allows for useful means in identifying the peak structural responses of linear single degree of freedom systems.

As shown in Figure 3, When analyzing all the physical data with SRS plots, it is clear that each accelerometer was showing the same modal behaviors with each CGT location. Each DOF checked, had very consistent frequency spikes, with only minor differences in the initial accelerations witch would have been caused by the slight variations in the magnitudes of the impulse loads for each CGT shot.

How high frequency can be considered is limited by the hardware collection frequency, the test structure is rather small so it's interesting frequencies may be above what the equipment can perceive. The same hardware may be more appropriate for larger, more realistic structures than this test structure, with lower natural frequencies. In only the X direction at the top of the wall is there a soft DOF. It is also noticeable that the lines for different tests only have a couple of distinct spikes and only the most general behavior is visible above about 100 Hz.

There is some suggestion that a split resonance present in a SRS can indicate the presence of an asymmetry in the boundary conditions, stiffness, or mass of a structure. The current test structure is symmetric and there was no split in the resonance to indicate this had occurred. A visual inspection indicated symmetric cracks on both walls, neither of which are wide enough to change the flexural behavior of the wall by much.

FINITE ELEMENT MODELING

A numerical model of the test structure was assembled in LS-DYNA to determine what behavior is being captured by the CGT pulse. This model included the walls and the slab, but did not include the drilled foundations below the slab. The concrete was modeled using constant stress eight node solid elements, the reinforcing steel is modeled as beam elements with the default 2x2 Gauss quadrature. A steel plate is used to impart the shock of the CGT. Like the plates used to mount the CGT to the structure, these steel plates are a square foot in dimensions and 0.5" thick. It is modeled using shells, using the default Belytschko-Tsay element formulation. All of the mesh size is 3", and all of the materials are defined as fully elastic, as the forces applied by the CGT are insufficient to push the material into its nonlinear range.

Material tests have not been performed on the test structure, so the elastic modulus of the steel was taken as a typical 29,000 ksi and the elastic modulus of the concrete was taken as 3,644 ksi, a typical value for a 4 ksi mix. The mass densities for the steel and concrete are 0.0089 lb/in^3 and 0.001235 lb/in^3 respectively. Damping was applied by part stiffness with a coefficient of 0.15. The bottom of the slab is restrained in all directions and the steel is constrained within the concrete using the BEAM_IN_SOLID constraint. The steel plate holding the CGT was constrained to the concrete at the appropriate location and the force applied evenly to the elements of the steel plate. Given the relative stiffness of the slab and piles compared to the relatively thin walls, the slab was rigidly restrained on the bottom.

Model Loadings

The recorded force pulse was quite noisy, with dynamic effects occurring almost immediately. There was a representative pulse that was simplified from the noisy output recorded during tests, as shown in Figure 2. When examining the raw data from the force pulses, there were some slight variations in the magnitudes of the pulse, but a consistent duration. Only one representative pulse must be defined for each thickness of aluminum and size of CGT. The SRS is robust to slight variations to magnitude, as the relative magnitude remains constant as the load is increased. This is visible in the physical tests, which have a slight difference in magnitude and are largely parallel to each other. The force recording at the CGT is quite noisy, fortunately, the modal reactions of the structure will be determined by the geometry and material definitions of the structure itself. So long as the CGT load is swift enough to activate all the modes, the response remains similar, a variety of pulse lengths were used, from the appropriate length to ten times as long as the recorded force and the modeled reaction remained similar. A trapezoidal pulse was used that reached its peak in 0.0002 seconds and stayed there for 0.0004 seconds before descending over another 0.0002 seconds.

COMPARISON OF MEASURED AND MODELED RESULTS

The model captured the general modal behavior of the test structure, with the SRS broadly matching for all the locations and directions tested. There were some limitations, the first CGT location was on the bottom slab. The simplified boundary conditions that had little effect when the CGT load was applied to walls but held the

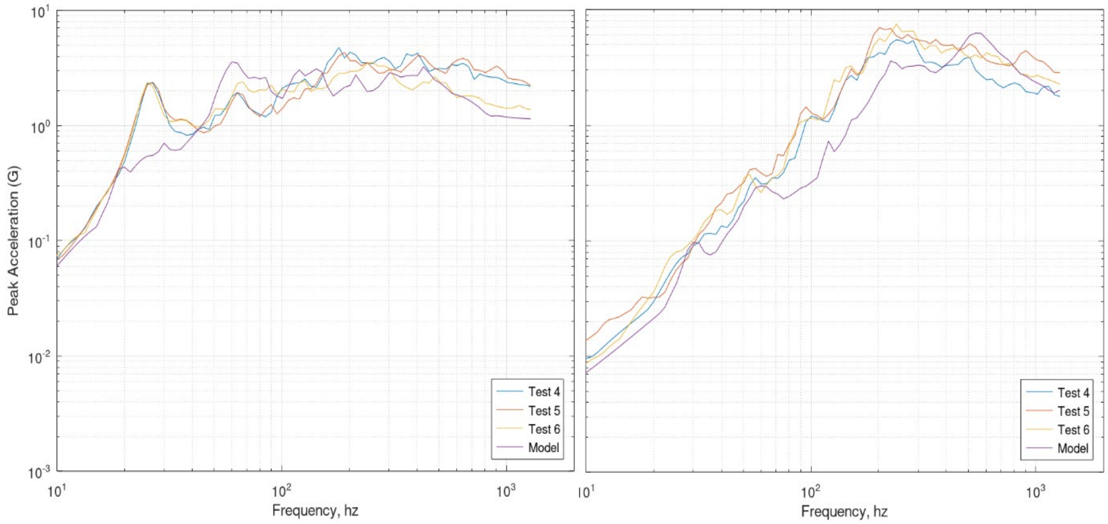

Figure 4. SRS for X and Y direction of Sensor Location 1 with CGT at location 2

slab somewhat too stiffly during these first tests. The rest of the tests applied the loads to the walls. Figure 4 shows the SRS of the first triaxial mount in the X and Y directions (orthogonal to the plane of the wall and placing the wall in shear respectively) and Figure 5 shows the SRS in the Z direction (up and down).

The X direction (orthogonal to the wall) has a consistent local maximum around 25 Hz. that indicates a natural frequency. In the model this is shifted over, indicating a somewhat stiffer wall then is modeled. This is seen in Figure 4, which shows the SRS for the X direction of triaxial location 1 for the 2nd CGT location alongside the modeled results. The model suggested the peak seen at 25 Hz. should be placed around 60 Hz. Before rejoining the tested results for frequencies over 100 Hz., detailed inspection of the test structure revealed vertical cracks in the wall, at approximately the halfway point

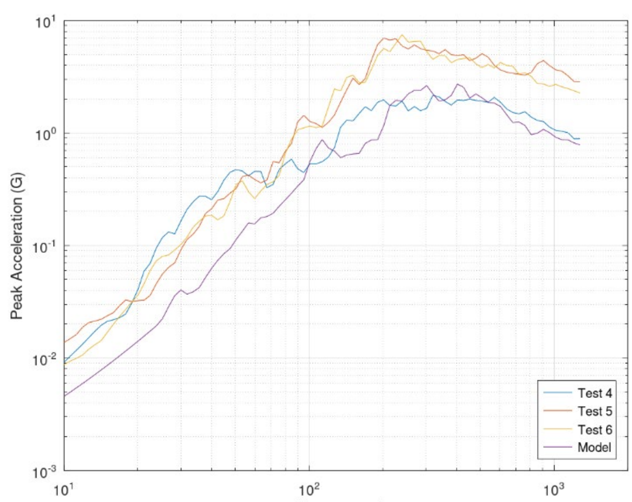

Figure 5. SRS for Z direction of Sensor Location 1 with CGT at location 2

present on both sides and reaching nearly from top to bottom, closing only 2 feet above the slab. However, the cracks were only about 0.0160" wide and such minor damage would not significantly change the modal behaviors of the structure, which are insensitive to local damage [4]. It may be the case that the stiffness of the piles is overestimated and the whole structure is vibrating through the soil, though if this is the case, it is odd the behavior is only apparent in the X direction

In the Y direction (placing the wall in shear) there is a local maximum between 50 and 60 Hz that is overrepresented in the model, both the model and the physical tests plateau their acceleration response at about 200 Hz, before moderately reducing the acceleration. Broadly, this matches in shape and does not suggest that a change in boundary condition has occurred. Unfortunately, no clearly shown natural frequency is seen in the Y or Z directions, so the behavior is less distinct. The Z direction both tests and models indicate a small increase in activity around 100 Hz, though not all tests indicate this.

CONCLUSION

The Performance Based Testing conducted on the reaction structure located at the Big Black Test Site is a technique that has a wide range of potential. The CGT mounted on all five locations of the reaction structure delivered clear acceleration responses that were investigated using the easily executed shock response spectrum analyses. The acceleration data captured exhibited a fairly broad range, with the highest and lowest accelerations response captured having a difference of 1.54 g`s. It is evident that the location of the CGT, along with the orientation of the funnel influenced the behavioral response of the structure, but the general modal behavior remained uninfluenced, whether the thruster was placed on the strongly restrained slab or the comparatively soft walls.

The empirical data gathered by the performance-based testing using the CGT was appropriate for calibrating a finite element model to capture general global behavior. Local additions of mass or cracks that only locally reduce the stiffness are likely to escape the results of any vibrational testing however and they remain so here. No global changes were induced to the structure so the magnitude of change necessary in that respect remains unknown.

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