SEISMIC EVALUATION OF LEAD CAVES USING NO-TENSION DISCRETE MODEL WITH INTERFACE ELEMENTS

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ABSTRACT
This paper investigates the quasi-static behavior of lead cave walls that are made by stacking lead bricks. These caves serve as radiation shields. The bricks have high stiffness, whereas the joints are weak and are incapable of supporting tension. The global behavior of this kind of wall is strongly influenced by the size and the coefficient of friction of the brick elements.

The general finite element code ANSYS was used for the analysis of the lead caves. A series of two-dimensional models that spanned the range of height-to-width aspect ratios of the cave wall were constructed. A single element was used for each brick. Each element is 20.3 cm (8.1 in.) long by 5.1 cm (2 in.) high. The joints are modeled by interface elements so that their deformability and frictional properties are taken into account. Two types of contact elements were incorporated in the model. The point-to-point contact element was used to represent contact in the horizontal direction. This element permits either compression in the direction normal to the surfaces or opening of a gap. The point-to-surface contact element was chosen to represent contact in the vertical direction. This element allows sliding in addition to the compression or gap formation normal to the surface.

A series of static analyses were performed for each model. A 1-g. vertical acceleration representing gravity was applied. The lateral acceleration was increased until the solution would not converge. This acceleration is defined as the critical lateral acceleration. This was achieved with a set of load steps with increasing lateral load. The critical acceleration was found to depend on the wall aspect ratio. For a wall with an aspect ratio up to three, the maximum acceleration is above the required 0.1 g. The wall failure mechanisms were also identified based on the numerical results. The two failure modes are the rotation and loss of interlocking among the blocks or sliding of upper layers of the wall.

INTRODUCTION
Lead caves are common structures at the U.S. Department of Energy's Hanford site. These are used for radiological counting, storage, and shielding from external radiation environments. These caves are formed by stacking lead bricks that serve as radiation shields. The purpose of this paper is to demonstrate the structural adequacy of lead caves to withstand earthquake ground motions. The lead caves in this study are treated as non-essential structures. Based on SDC-4.1, Standard Arch-Civil Design Criteria (Kaiser Engineers Hanford 1993), these caves need to withstand at least 0.09 g seismic acceleration in the horizontal direction and 0.06 g in the vertical direction.

The objective of this paper is to document the analyses that were performed to seismically qualify the lead cave.
structures. The focus of this work was to establish safe g-levels that might occur during a seismic event. The structures that were analyzed were 1.2 to 2.4 m (4 to 8 ft.) high, 1.2 to 1.5 m (4 to 5 ft.) deep, and had a length between 1.2 and 7.3 m (4 and 24 ft.). The dimensions of the individual caves are specified in PNL Drawing No. WS-330-94 (Pacific Northwest Laboratory 1994). Portions of these structures have steel plates to support the brick layers to form various compartments and also to support the roof. All these caves have covers (roofs) that are typically formed by stacking two layers of lead bricks. The bricks are 5.1 cm (2 in.) high, 10.2 cm (4 in.) wide, and 20.3 cm (8 in.) long so that as many as 50 layers of these bricks are used in the tall caves.

For rigid bodies that are not anchored to the ground, the two response modes to earthquakes are sliding and rocking. The rocking mode is particularly critical for the taller caves. It was determined that caves less than 1.2 m (4 ft.) tall are not deemed critical in terms of the danger of overturning because of the seismic loads. One set of hand calculations was conducted to indicate the level of friction required to prevent sliding on a macro scale. A second set of calculations indicated the margin of safety with regard to rocking failure.

Non-conservative assumptions made in the hand calculations suggest that more detailed finite element analyses were appropriate for accurate resolution of this problem. An analysis documented in Trovalusci (1992) considered a similar problem specifically directed toward the analysis of ancient masonry wall. That analysis defined the bricks with constraint equations and used no-tension interface elements to allow separation and rotation of the bricks.

Two types of finite element models were constructed to analyze the lead caves. Two-dimensional models were assembled to investigate the in-plane or shear behavior of an individual wall. The conservative assumption of no support from the neighboring wall was made. Three-dimensional models were assembled to investigate the out-of-plane behavior of a wall. Again, the model did not consider any support from the adjoining wall.

METHODS OF ANALYSES

A series of calculations were conducted as a scoping tool to obtain a feel for the problem. These followed the procedures outlined by Aslam, Godden, and Scalise (1975 and 1978). The potential for rocking was evaluated based on equilibrium considerations. The effect of the static coefficient of friction on a single block was the basis for evaluating sliding. These simplified analyses concluded that all the lead caves would withstand the required seismic excitation. The simultaneous horizontal and vertical earthquake motions would not induce failure either by rocking or sliding.

Rocking was treated in a manner analogous to beam bending. Each cave was treated as a continuous structure such that a moment of inertia could be calculated. The specified seismic accelerations were multiplied by the total mass and applied at the computed centers of gravity to obtain the applied moments. These moments were treated as generating tensile stresses in the vertical direction of the cave walls. These stresses were compared with the compressive stresses produced by gravity. In each cave the compressive stresses exceeded the tensile stresses, indicating that rocking would not occur.

Sliding was assessed by evaluating the forces on a single block. Sliding will occur when the horizontal force caused by the lateral seismic acceleration exceeds the effective frictional force. It was observed that sliding would not occur for any reasonable values for the coefficient of friction.

While these calculations provided a first approximation to the seismic qualification problem, the imprecision of the assumptions indicated that a more precise analysis was required. In particular, the assumption of a continuous structure that could develop tensile stresses was extremely artificial. It was decided that a finite element model incorporating no-tension interface elements would accurately handle this difficulty. This model would allow gaps to open between adjacent bricks, both in the horizontal and vertical directions.

Finite Element Models

Revision 5.0 of the ANSYS (Swanson Analysis Systems, Inc. 1992) general-purpose finite element program was used for the finite element analysis of the lead caves. A series of two-dimensional models that spanned the range of height-to-width aspect ratios of the cave walls was constructed. The four-node plane42 element was used to represent the bricks. A single element was used for each brick. Each element was 20.3 cm (8 in.) long by 5.1 cm (2 in.) high. The plane stress with thickness (depth) option was selected to allow accurate representation of the wall. The depth was specified to be 10.2 cm (4 in.).

The models used parametric input such that the aspect ratio of the wall could be changed readily. One series of models was based on a five-brick-wide [1 m (40 in.)] base. Figure 1 shows the model used for the 1:1 aspect ratio. Computer run times became prohibitive at the higher aspect ratios, so the model was revised to be three-bricks [61 cm (24 in.)] wide. Figure 2 shows the 3:1 aspect ratio model. Analyses of each model at identical aspect ratios were conducted to ensure that the same results were being given.
Additional models considered the effects of a steel plate both on top of the wall and also at the base. The plate was modeled with a single element, 2.5 cm (1 in.) high, spanning the width of the wall. The depth of the plate at the top of the wall was 30.5 cm (12 in.). This provided a weight somewhat representative of the steel plates in the actual caves.

Two types of contact elements were incorporated in the model. The contact12 point-to-point contact element was used to represent contact in the horizontal direction. This element permits either compression in the direction normal to the surfaces or the opening of a gap. The force-deflection relationship for this element is shown in Figure 3. The local surface deformations were not important, so the normal stiffness was specified as two orders of magnitude larger than the adjacent element stiffness. This element also supports sliding friction, but this capability was not required for this application.

The contact48 2D point-to-surface contact element was chosen to represent contact in the vertical direction. This element is particularly suited to models where the contact location may change significantly during the analysis. Sliding is allowed in addition to compression or gap formation normal to the surface. Elastic Coulomb friction was included by defining the coefficient of friction as described in the section on material properties. The element normal stiffness was again defined to be about two orders of magnitude larger than the adjacent element stiffness.
This element is defined by three nodes. The "contact surface" is defined by a single node, which may come in contact with the "target surface" defined by two nodes. For this problem, symmetric contact was defined such that each surface was in turn both the "contact surface" and the "target surface." The distinction between near-field and far-field contact-surface location is the first step in the element-solution procedure. Near-field contact is further evaluated by means of a pseudo-element algorithm to determine if penetration has occurred. The gap or penetration is then evaluated in the element local coordinate system.

The combined penalty function plus Lagrange multiplier method was used to determine contact forces. This option allows for quicker convergence while maintaining accurate results. The tolerance in the direction of the surface normal was varied to ensure that sufficient accuracy was kept. The option to use contact-time predictions was also used to optimize the automatic time stepping to accelerate convergence.

The lengths of the target surfaces were internally increased by 5%. This was required, at the edges of the model where node-to-node contact was present, to ensure convergence. The solution tended to oscillate without this option, making convergence difficult.

The three-dimensional models incorporated the eight-node solid45 element to represent the bricks. Again, a single element was used for each brick. This gave the basic element dimensions of 20 cm (8 in.) length, 5.1 cm (2 in.) height, and 10.2 cm (4 in.) depth. Parametric input was used to allow for convenient changes to the wall aspect ratio. Figure 4 shows the model used for the 1:1 aspect ratio. The additional computer run time for higher aspect ratio models again forced the use of a three-brick-wide model. Figure 5 shows the 2.33:1 aspect ratio model.

These models required the use of the contact49 3D point-to-surface contact elements to handle the vertical contact. This element is the 3D version of the contact48 element. It is essentially identical in concept and operation as the 2D element, but requires four nodes to define the "target surface."

**Material Properties**

The modulus of lead was taken to be 2,000,000 psi. The density of lead was specified as 0.4 lb/in³. A brief literature review revealed a broad range of values for the coefficient of friction for lead on lead. Fuller (1984) gives a range from 0.39 to 3.30! Rabinowicz (1965) states a value of about 1.2 for clean unlubricated lead. He also emphasizes the significance of the surface films. A value of 0.6 was selected as the baseline for these analyses. A set of analyses was conducted with \( \mu = 0.4 \) for comparison.
Loads and Boundary Conditions
A series of static analyses were performed for each 2D model. The nodes at the bottom of the model were constrained in all directions. The gravity load was represented by a vertical body force of 1 g. A lateral acceleration was then applied in increasing load steps until the solution would not converge. This acceleration is defined as the critical lateral acceleration. This loading scenario was achieved by using a set of load steps with the lateral load increasing $5 \times 10^8$ g each step. This step size was chosen to ensure convergence.

The procedure for the 3D analyses followed a somewhat different approach. The nodes at the base of the wall were again constrained in all directions. The extended execution time of the 3D analyses precluded the step-wise definition of the critical lateral acceleration. The approach taken was to directly apply the body force loads specified by the requirement.

RESULTS AND DISCUSSION
The equation defining rocking of a single block can be determined by considering the equilibrium of forces. The block will be on the verge of rocking when the moment because of the horizontal inertia force about one edge is equal to the restoring moment due to the vertical inertia force about the same edge. Thus:

$$
\ddot{a} = \left(\frac{B}{H}\right) g \left(1 + \frac{\ddot{v}}{g}\right)
$$

where $\ddot{a}$ is the horizontal acceleration, $\ddot{v}$ is the vertical acceleration, and $B$ and $H$ are the width and the height of the block.

The dependence on the height-to-width aspect ratio of the block is clear. This relationship can be extended to an entire wall. Therefore, finite element analyses of a range of aspect ratios was conducted. The aspect ratio of the wall is the significant factor, rather than the actual dimensions of the wall.

The onset of sliding of a single block can be determined by equating the horizontal force with the frictional force. Consequently:

$$
\ddot{a} = \mu g \left(1 + \frac{\ddot{v}}{g}\right)
$$

where $\mu$ is the coefficient of friction.

This indicates that sliding is governed by the coefficient of friction independent of block size or aspect ratio.

The results of the 2D analyses without the steel plate are plotted in Figure 6. The results are presented in terms of critical lateral acceleration as a function of aspect ratio. It is clear that all the lead caves can withstand lateral accelerations well in excess of those specified for a seismic event. There are two distinct regions of failure. At low aspect ratios, the critical lateral acceleration is constant and is equal to the coefficient of friction times the vertical acceleration. The critical acceleration decreases at higher aspect ratios. There is insufficient data to definitively describe the wall behavior at higher aspect ratios; however, a linearly decreasing relationship could reasonably be postulated.

Figure 7 shows the results of the analyses of the wall with steel plates on the top and at the bottom. The results of the 0.4 brick coefficient of friction analysis are also plotted for reference. The lower coefficient of friction between the steel and the lead governs the failure load of these designs. The critical lateral acceleration is constant at $\mu g$ for the lower aspect ratios.

Consideration of a single block suggests that the "failure" mode will change from sliding to rocking when the aspect ratio exceeds $1/\mu$. Review of the finite element results indicates that the "failure" mode will switch at a lower aspect ratio than this. Figure 8 is a displacement plot of the 2.5 aspect ratio wall with $\mu = 0.4$ at a lateral acceleration of 0.3 (just before failure). The displacements have been magnified on the plot, but lateral shifting, although small, has already occurred. The formation of lateral gaps between bricks in the lower layers is evident.

Changing the coefficient of friction between the bricks changes the initial sliding portion of the failure curve. It appears to have little effect on the rocking portion, although there is insufficient data to reach firm conclusions.

CONCLUSIONS
All the caves considered in this study meet the requirements of the Hanford Design Criteria with regard to seismic events. The results are sensitive to the values assumed for the coefficient of friction. However, for the aspect ratios of the caves considered in this study, the critical coefficient of friction is well below any actual values.

REFERENCES


Figure 6. Critical Lateral Acceleration

Figure 7. Critical Lateral Acceleration Base Plate
Figure 8. Displacement Plot


